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Hamstring Strain Injury:

Rate of Torque Development and Previous Hamstring Strain Injury

Dissertação elaborada com vista à obtenção do Grau de Mestre em Treino de Alto Rendimento

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"A alegria está na luta, na tentativa, no sofrimento envolvido e não na vitória propriamente dita."

Mahatma Gandhi

Abstract

Hamstring strain injuries (HSI) are extremely common in football and are the primary cause of re-injury in football players. Although the isokinetic strength ratios have often been used to predict hamstring injuries in football players, the rate of torque development hamstring to quadriceps ratio (RTD H/Q) has rarely been considered in previous reports. Furthermore, little consideration has been given to selective hamstring lengths and their influence on torque production and knee muscle balance, especially under muscle fatigue condition in previously injured hamstrings.

Thus, the present dissertation contemplated two approaches. The first, presented in Chapter 3, which aimed to determine the RTD H/Q at long hamstring lengths and the conventional (concentric/concentric) and functional (eccentric/concentric) hamstrings/quadriceps (H/Q) ratios. The second approach, presented in Chapter 4, aimed to determine the effect of muscle fatigue, induced by a specific protocol seeking to mimic the loads and characteristics of team sports, on the knee muscle balance, given by the RTD, conventional and functional hamstrings/quadriceps (H/Q) ratio.

Twenty-four professional men's football players, divided into two experimental groups, with (PI) and without (UG) previous HSI, competing in the 1st and 2nd national leagues, participated voluntarily in the studies (approved by the local ethical council – CEFMH: 13/2018). Players performed both quadriceps and hamstring maximal voluntary isometric contractions at 30º of knee flexion (long hamstring lengths) and maximal concentric isokinetic contractions at $180°.s^{-1}$ and $60°.s^{-1}$. Isokinetic eccentric contractions at $180°.s^{-1}$ and $60°.s^{-1}$ of hamstring muscles were also performed. Conventional and functional H/Q ratios based on peak torque throughout the entire isokinetic range of motion and at 30° of

knee flexion were calculated. Long hamstring lengths RTD H/Q ratios were extracted at incrementing time periods of 50 milliseconds (ms) from the onset of contraction (50-250 ms).

The main findings showed that players with a previous HSI (PI) have a small effect towards lower eccentric torque and RTD H/Q at the initial period of contraction (50 ms, $p > 0.05$, $d = 0.4$). The PI also showed small to moderate ($0.4 > d < 0.6$) higher rate of torque development ratios in late time intervals (>100 ms) as well.

Following fatigue, significant differences were found between groups (PI and UG) in the RTD H_{50}/Q_{50} ratio ($p < 0.05$; $d = 1.0$). Previous hamstring strain injury group showed small to moderate ($p > 0.05$; $0.3 > d < 0.6$) lower RTD H/Q ratios in early time intervals (<150 ms) as well (<150 ms).

In conclusion, to the best of our knowledge, these were the first studies to investigate the rapid H/Q ratio at long hamstring lengths in professional football players with previous HSI. The findings presented in this dissertation may have important implications for future injury prevention and rehabilitation programs and for the explosive strength improvement of the hamstrings. Future studies should also investigate whether lower RTD H/Q ratios are an adaptation to injury, or if it's a risk factor to future HSI. Also, future studies should seek to investigate whether training in a fatigue state reduces the injury incidence, and, if successful redirect new injury prevention guidelines, to help reduce the large (re-)injury rates of HSI in professional football.

Keywords: explosive strength, hamstring strain, professional football, hamstring strength, muscle strain, long hamstring length, fatigue, rate of torque development, rate of force development, neuromuscular inhibition

Resumo

As roturas dos isquiotibiais (RISQ) são extremamente comuns no futebol e representam a primeira causa de recidiva de lesão em jogadores de futebol. Apesar dos rácios isocinéticos entre isquiotibiais e quadricípites (rácios ISQ:QUAD) serem amplamente divulgados na literatura como preditores de RISQ, o rácio para a taxa de produção de força (TPF ISQ:QUAD) tem sido muito raramente referenciado em investigações anteriores. Além disso, pouca relevância tem sido dada à influência do estado de alongamento dos ISQ na capacidade de produção de força e no equilíbrio funcional do joelho, sobretudo num contexto de fadiga muscular em isquiotibiais previamente lesionados.

Deste modo, a presente dissertação contemplou duas abordagens. Uma primeira, (Capítulo 3), procurou determinar o TPF ISQ:QUAD em condição de alongamento dos ISQ, assim como os tradicionais rácios ISQ:QUAD convencional ($ISQ_{conc}/QUAD_{conc}$) e funcional ($ISQ_{exc}/QUAD_{conc}$). A segunda abordagem (Capítulo 4), procurou determinar o efeito da fadiga muscular, induzida por um protocolo específico envolvendo ações caraterísticas da modalidade, no equilíbrio muscular e funcional da articulação (rácios ISQ:QUAD convencional, funcional e da TPF).

Vinte e quatro jogadores profissionais de futebol, divididos em dois grupos experimentais, com (PI) e sem (UG) historial prévio de RISQ, com prática competitiva atual nos campeonatos das 1ª e 2ª ligas nacionais, participaram voluntariamente nos estudos. Foram realizadas contrações isocinéticas concêntricas (QUAD e ISQ) e excêntricas (ISQ) a $180°.s^{-1}$ e $60°.s^{-1}$ e contrações isométricas máximas (QUAD e ISQ) a 30º de flexão do joelho. Os rácios convencional e funcional foram calculados com base no momento de força máximo obtido em toda a janela isocinética e a 30º de flexão do joelho. O TPF ISQ:QUAD foi calculado em intervalos incrementais de 50 milissegundos (ms) a partir do instante inicial de contração (50-250ms).

Os principais resultados revelaram que jogadores com historial de RISQ (PI) apresentam ligeiro efeito para um reduzido momento de força excêntrico e do TPF ISQ:QUAD no período inicial de contração (50ms; $p>0,05$; $d=0,4$). O PI revelou ainda um pequeno a moderado efeito ($p>0,05$; $0,4>d<0,6$) para rácios TPF ISQ:QUAD superiores em períodos mais tardios da contração muscular (>100ms). Em condição de fadiga, foram observadas diferenças significativas entre grupos no rácio TPF ISQ:QUAD aos 50ms ($p<0,05$; $d=1,0$). Foram ainda encontradas pequenos a moderados efeitos ($p>0,05$; $0,3>d<0,6$) para rácios TPF ISQ:QUAD inferiores nos períodos prematuros da contração (<150ms).

Em conclusão, este foi o primeiro estudo a investigar o rácio para a TPF ISQ:QUAD em condição de alongamento dos ISQ em jogadores profissionais de futebol com historial de RISQ. Os resultados encontrados podem ter implicações futuras nos programas de prevenção e reabilitação de lesão e no desenvolvimento da força explosiva dos ISQ. Estudos futuros devem investigar a verdadeira origem dos desequilíbrios evidenciados neste estudo, analisando se decorrem de uma adaptação à própria lesão, ou se poderão decorrer da prática desportiva e do processo de treino. A influência da fadiga na incidência de lesão também deve ser investigada. Se bem-sucedidos, estes estudos poderão fornecer novas diretrizes sobre a prevenção de rotura dos ISQ.

Palavras-chave: força explosiva, rotura dos isquiotibiais, futebol profissional, força dos isquiotibiais, rotura muscular, comprimento muscular dos isquiotibiais, fadiga, taxa de produção de momento de força, taxa de produção de força, inibição neuromuscular

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List of Acronyms

BFlh	biceps femoris long head
BFsh	biceps femoris short head
Ca^{2+}	calcium
CMJ	countermovement jump
Conc	concentric
Ecc	eccentric
FAST-FP	functional agility short-term fatigue protocol
HAMS	hamstrings
HSI	hamstring strain injuries
H/Q	hamstrings to quadriceps ratio
$H_{conc180}/Q_{conc180}$	conventional hamstrings to quadriceps ratio at an angular velocity of $180^{o}.s^{-1}$
$H_{conc180}/Q_{conc180}$ @ 30º	conventional hamstrings to quadriceps ratio at an angular velocity of $180^{o}.s^{-1}$ based on peak torque values at 30º knee flexion
H_{conc60}/Q_{conc60}	conventional hamstrings to quadriceps ratio at an angular velocity of $60^{o}.s^{-1}$
H_{conc60}/Q_{conc60} @ 30º	conventional hamstrings to quadriceps ratio at an angular velocity of $60^{o}.s^{-1}$ based on peak torque values at 30º knee flexion
$H_{ecc180}/Q_{conc180}$	functional hamstrings to quadriceps ratio at an angular velocity of $180^{o}.s^{-1}$
$H_{ecc180}/Q_{conc180}$ @ 30º	functional hamstrings to quadriceps ratio at an angular velocity of $180^{o}.s^{-1}$ based on peak torque values at 30º knee flexion
H_{ecc60}/Q_{conc60}	functional hamstrings to quadriceps ratio at an angular velocity of $60^{o}.s^{-1}$

$H_{ecc180}/Q_{conc180}$ @ 30º	functional hamstrings to quadriceps ratio at an angular velocity of 60º.s^{-1} based on peak torque values at 30º knee flexion
H_{MVIC}/Q_{MVIC}	hamstrings to quadriceps ratio based on maximal voluntary contraction values
MU	motor unit
MVIC	maximal voluntary isometric contraction
Nm	Newton meter
PI	previously injured group
pRTD	peak rate of torque development
QUAD	quadriceps femoris
RFD	rate of force development
RTD H/Q	rate of torque development hamstrings to quadriceps ratio
RTD $H_{0\text{-}50}/Q_{0\text{-}50}$	rate of torque development hamstrings to quadriceps ratio at 50 milliseconds
RTD $H_{0\text{-}100}/Q_{0\text{-}100}$	rate of torque development hamstrings to quadriceps ratio at 100 milliseconds
RTD $H_{0\text{-}150}/Q_{0\text{-}150}$	rate of torque development hamstrings to quadriceps ratio at 150 milliseconds
RTD $H_{0\text{-}200}/Q_{0\text{-}200}$	rate of torque development hamstrings to quadriceps ratio at 200 milliseconds
RTD $H_{0\text{-}250}/Q_{0\text{-}250}$	rate of torque development hamstrings to quadriceps ratio at 250 milliseconds
SD	standard deviation
SM	semimembranosus
ST	semitendinosus
UG	uninjured group

Chapter 1: Introduction

INTRODUCTION

Hamstrings strain injuries represents the most common injury in professional football, with a prevalence of 12% (Jan Ekstrand, Hagglund, & Walden, 2011; Jan Ekstrand, Hägglund, & Waldén, 2011; Woods, 2004). Furthermore the relatively high re-injury rates (12-16%) (Jan Ekstrand et al., 2012, 2011; Woods, 2004) are perhaps the most concerning aspect of these injuries, as re-injuries are usually more severe, and lead to more time absent from sport practice than previous insults (Brooks, Fuller, Kemp, & Reddin, 2006; Jan Ekstrand et al., 2011). Moreover, an average of 5-7 HSI, accounting for a total of 82-90 days of absence and 15 matches missed per club, per season, should be expected in a squad of 25 players (Jan Ekstrand et al., 2011; Woods, 2004). However, despite the extensive literature about HSI, injury incidence have not declined, in fact it´s rising 4% anually (Jan Ekstrand, Waldén, & Hägglund, 2016). Given this, the injury burden (given by the cross-product of severity and incidence) of all football injuries suggests that attention must be given to HSI (Bahr, Clarsen, & Ekstrand, 2017).

In order to succesfully reduce the amount of HSI (re-)injury rates correct understanding of the underlying mechanisms and risk factors is critical for developing sucessful prevention and rehabilitation programs. High-speed running is the most commnon mechanism of injury reported in the literature (Elliott, Zarins, Powell, & Kenyon, 2011a; Woods, 2004). Actually, Woods (2004) found that ~60% of HSI ocurred during running actions. The late swing phase is perpetuadet as the most prone to injury due to the high amount of strain placed upon the biarticular hasmtring muscles at peak muscle lengths (Heiderscheit et al., 2005; Thelen et al., 2005; Yu et al., 2008). Also, several risk factors have been extensively proposed in the literature, such as age (Freckleton & Pizzari, 2013; Fyfe, Opar, Williams, & Shield, 2013; Opar, Williams, & Shield, 2012), ethnicity (Fyfe et al., 2013), insufficient warm-up (Woods, 2004), poor flexibility (Fyfe et al., 2013; Woods, 2004), muscle imbalances (Lee, Mok, Chan, Yung, & Chan, 2017; Woods, 2004), muscle weakness (Fyfe et al., 2013; Lee et al., 2017; Woods, 2004), neural tension (Woods, 2004) and fatigue (Fyfe et al., 2013; Woods, 2004). However, the previous injury remains as the main risk factor (Arnason et al., 2004; Fyfe et al., 2013; Lee et al., 2017; Mair, Seaber, Glisson, & Garrett, 1996) increasing two to three times the likelihood to suffer an identical injury (Hägglund, Waldén, & Ekstrand, 2006).

Isokinetic knee muscle strength have been traditionally used as screening tool for indentifying athletes in risk of future HSI (J. L. Croisier, Ganteaume, Binet, Genty, & Ferret, 2008; Van Dyk et al., 2016a), as well as previous injury (Lord, Ma'ayah, & Blazevich, 2018), despite the contradictory literature (Green, Bourne, & Pizzari, 2018; Opar et al., 2012). A possible explanation to the inconsistent results found in the literature could be the fact that the time-wise nature of the proposed mechanism of injury (e.g. high-speed running) usually occurs in less than 250 milliseconds (ms) (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Maffiuletti et al., 2016; Rodríguez-Rosell, Pareja-Blanco, Aagaard, & González-Badillo, 2017). whereas maximal muscle strength is not attained in less that 300-500 ms following the onset of contraction (Aagaard et al., 2002). Furthermore, Opar et al., (2013) found lowered rate of torque development during hamstring eccentric contractions in previously injured hasmtrings (Opar, Williams, Timmins, Dear, & Shield, 2013). However, peak hasmtring elongation is found during the late swing phase (~30º of knee flexion) of high-speed running (Heiderscheit et al., 2005; Thelen et al., 2005; Yu et al., 2008) Indeed, little to no consideration has been given to this selective hasmtring length when measuring hasmtring strength. In fact, Sole et al., (2011) found a selective inability to activate the hamstrings towards greater muscle lengths (Sole, Milosavljevic, Nicholson, & Sullivan, 2011). Addtionally, fatigue was found to decline more eccentric hasmtring strength (Greig, 2008; Rahnama, Reilly, Lees, & Graham-Smith, 2003) as well as running kinematics, increasing knee extension angles during the late swing phase (Pinniger, Steele, & Groeller, 2000) which may may explain why HSI ocurrence increases towards the end of each half of the football match (Woods, 2004) Given this, we suggest that the rapid hamstrings to quadriceps strength ratio (RTD H/Q) (Zebis, Andersen, Ellingsgaard, & Aagaard, 2011), especially at long hamstrings lengths and under muscle fatigue, could be of significant importance in order to study the adaptations of previous HSI in hamstrings explosive strength, as well as the effects of fatigue in this rapid knee muscle balance screening tool.

Thus, the general purpose of this thesis is to characterize the rapid hamstrings to quadriceps ratio in professional football players with previous HSI. Regarding the fact that 1) a selective inability to activate the hamstring at long lengths (Sole, Hamrén, Milosavljevic, Nicholson, & Sullivan, 2007), 2) a concomitant atrophy of the long head, and hypertrophy of the short head of the biceps femoris (Silder, Heiderscheit, Thelen, Enright, & Tuite, 2008) and 3) lower rate of torque development (Opar et al., 2013) was found in previously injured hamstrings, the rapid hamstrings to quadriceps ratio could be a sensitive tool to assess possible maladaptation following HSI. Thus we intended to answer the following questions:

- Does previously injured hamstrings players have a lower RTD H/Q ratios at long muscle lengths?
- Does previously injured hamstrings have lower concentric and eccentric peak torques?

- Does previously injured hamstrings have lower conventional and functional H/Q ratios?
- Does fatigue influence RTD H/Q ratios at long muscle lengths in previously injured hamstrings?

To answer the above mentioned questioned two studies were conducted:

1. Rapid hamstrings to quadriceps ratio at long muscle lengths in football players with previous HSI (Chapter 3).

2. Does fatigue impair rapid hamstrings to quadriceps ratio at long muscle lengths in professional football players with previous HSI? (Chapter 4)

Chapter 2: Review of the Literature

REVIEW OF THE LITERATURE

2.1. Classification and Incidence of Muscle Strain Injuries

Muscle strain injuries occur when the muscle fibers cannot withstand the excessive tensile forces placed upon them (Askling, Malliaropoulos, & Karlsson, 2012; Askling, Tengvar, Saartok, & Thorstensson, 2007). Hence, muscle strains are generally associated to eccentric muscles actions where the muscles have to contract forcefully while being lengthened (Roig & Ranson, 2007). Moreover, strain injuries usually occur in muscles working across two joints (e.g. biarticular) during periods where they have to rapidly accelerate/decelerate the movement across two joints, resulting in a lengthened state of the contracting muscles (Askling et al., 2012, 2007). Muscle stains can be divided into three grades, according to the severity of injury (Blankenbaker & Tuite, 2010; Jan Ekstrand et al., 2012), as either:

- Grade I: where minimum tear to the musculotendinous unit occurs and minor loss of strength,
- Grade II: where a partial tear to the musculotendinous unit and significant loss of strength, resulting in loss of function and,
- Grade III: where a complete rupture of the musculotendinous unit occur resulting in severe functional limitations;

As soon as the injury occur, neutrophils initiate the inflammation process and the phagocytosis of the injured muscle fibers (Dueweke, Awan, Mendias, Arbor, & Physiology, 2018). Soon after, macrophages help to promote tissue repair and regeneration, by signaling satellite cell proliferation (Dueweke et al., 2018). This process leads to the formation of scar tissue, very important in early healing, however if not correctly addressed can become permanent and lead to reduced flexibility due to his inelastic characteristics and, if left unattended, can increase the likelihood of re-injury (Fyfe et al., 2013; Järvinen, Järvinen, Kääriäinen, Kalimo, & Järvinen, 2005).

2.2. Incidence of hamstring strain injury

There is a high incidence of HSI in sports that involve high-speed running such as football (Jan Ekstrand et al., 2011; Woods, 2004), athletics (Opar et al., 2012), American football (Elliott, Zarins, Powell, & Kenyon, 2011b) and rugby (Brooks et al., 2006). In professional football, hamstring injuries have been reported to represent 12% of lower limb muscle injuries (Jan Ekstrand et al., 2011; Jan Ekstrand et al., 2011; Woods, 2004). Time lost and injury recurrence are also amongst the highest, even after rehabilitation programs, with a recurrence rate of 12-16% (Jan Ekstrand et al., 2012, 2011; Woods, 2004). Over the last years of injury surveillance, hamstring injuries have remained on average of 5-7 HSI, accounting for a total of 82-90 days of absence and 15 matches missed per club, per season in a squad of 25 players (Jan Ekstrand et al., 2011; Woods, 2004). In addition the biceps femoris alone accounts for 53% of all HSI while the semimembranosus and semitendinosus account for only 13% and 16%, respectively (Askling et al., 2007; Woods, 2004). First-time HSI may incur in several weeks and games of missed practice, however perhaps the most concerning effect of these is the high propensity for recurrence (J.-L. Croisier, 2004), as subsequent injuries are generally more severe than the initial injury, leading to more time lost, and higher costs (Jan Ekstrand et al., 2011; Hägglund et al., 2006).

Strains to the hamstring muscle group usually occur at the muscle-tendon junction (Garrett WE, 1996). The proximal regions of the hamstrings are the most affected, more so than the distal region, whereas the action being performed at the time of injury can be associated to the region affected (Askling et al., 2012). Askling et al., (2012) stated that the closer to the origin of the hamstring muscles (ischial tuberosity) the longer the rehabilitation period. However, magnetic resonance imaging diagnosis is only used in ~5% of all HSI in professional football (Woods, 2004). Muscular strain injuries are mainly associated with non-contact mechanisms (Hawkins et al., 2001; Woods, 2004).

2.3. Mechanisms of hamstring strain injury (HSI)

Numerous mechanisms have been associated with hamstring injuries, including stretch maneuvers in ballet, rapid changes of direction, tackling, however, the primary mechanism reported in professional football is the high-speed running (Askling et al., 2012; Brooks et al., 2006; Woods, 2004, Figure 1).

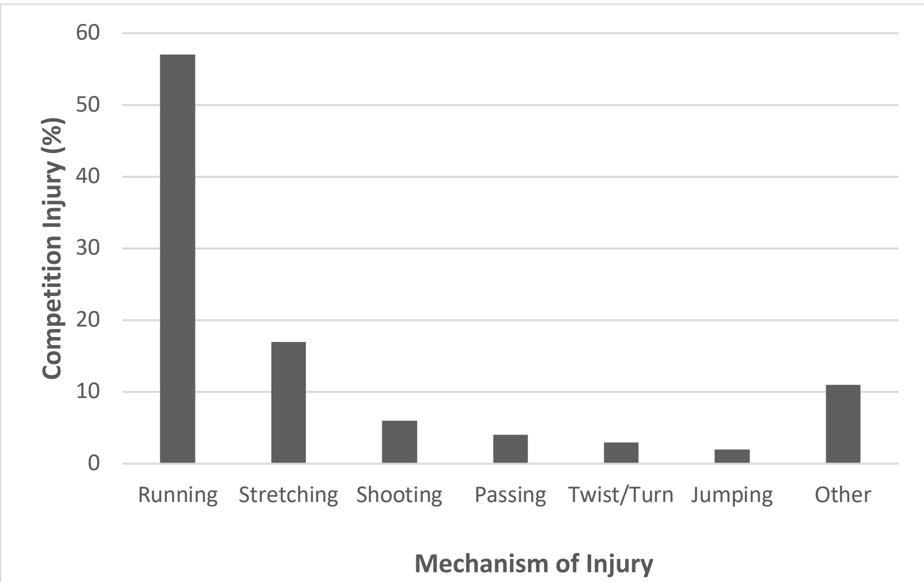

Figure 1: Mechanism of hamstring injuries, adapted from Woods (2004).

Given this, several biomechanical analysis of the hamstring function during running have been made over the last years (Chumanov, Heiderscheit, & Thelen, 2011; Heiderscheit et al., 2005; Schache, Dorn, Blanch, Brown, & Pandy, 2012; Thelen et al., 2005; Yu et al., 2008). The terminal swing phase have been proposed as the most potentially injurious phase of the running gait (Chumanov et al., 2011; Heiderscheit et al., 2005; Thelen et al., 2005). During this phase of the running gait the hamstring muscles need to rapidly decelerate the extending knee and advancing thigh (Thelen et al., 2005). This results in the hamstrings contracting forcefully while being lengthened, moreover, acting across two joints, all mechanisms, above mentioned, of the muscle strain injuries. Moreover, this action usually occur in less than 250ms which strongly suggests that the hamstrings need to rapidly contract during running (Aagaard et al., 2002). This notion leads to the rate of force development capabilities of the hamstring muscles, which will be further discussed below.

2.4. Etiology of hamstring strain injuries (HSI)

2.4.1. Anatomy of the hamstrings

The hamstring muscles are composed by three separate muscles: biceps femoris (long and short heads), semitendinosus and semimembranosus (Garrett, Califf, & Bassett, 1984). All originate at the ischial tuberosity, although the biceps femoris has two heads with the second, the short head, originating from the linea aspera and lateral supracondylar line of the femur. The semimembranosus attaches into the posterior part of the medial tibial condyle and the oblique popliteal ligament, the semitendinosus into the antero-medial surface of the tibia while the biceps femoris long and short head attaches onto the head of the fibula (Correia & Espanha, 2010). Since the muscles cross two joints (hip and knee), they have a dual role acting as either a hip extensor and knee flexor (Correia & Espanha, 2010). The hamstring muscles innervation is made through the tibial branch of the sciatic nerve (L5, S1, S2 and S3) to the semitendinosus, semimembranosus and the long head of the biceps femoris. Its short head is innervated trough the peroneal branch of the sciatic nerve (L5, S1, S2) (Markee et al., 1955). The biceps femoris, therefore, has a dual-innervation. In certain activities, this dual-innervation and multiarticular characteristic of the biceps femoris can lead to different actions in each joint causing an overstretch of the musculotendinous unit which can increase the susceptibility of a muscle strain injury (Liu, Garrett, Moorman, & Yu, 2012). The hamstrings muscles can produce large amounts of forces, beneficial to rapid sprinting, accelerations/decelerations and quick changes of direction due to its predominantly type 2 fiber composition, however, they also fatigue rapidly.

2.4.2. Risk factors

The multifaceted nature of HSI has led to several risk factors being reported in the literature. Some of the proposed risk factors are non-modifiable, such as age (Freckleton & Pizzari, 2013; Fyfe et al., 2013; Opar et al., 2012), ethnicity (Fyfe et al., 2013) and previous injury (Arnason et al., 2004; Fyfe et al., 2013; Mair et al., 1996; Woods, 2004). While modifiable risk factors include insufficient warm-up (Woods, 2004), poor flexibility (Fyfe et al., 2013; Woods, 2004), muscle imbalances (Lee et al., 2017; Woods, 2004), muscle weakness (Fyfe et al., 2013; Lee et al., 2017; Woods, 2004), neural tension (Woods, 2004) and fatigue (Fyfe et al., 2013; Mair et al., 1996; Woods, 2004). However, previous injury remains as the main risk factor (Arnason et al., 2004; Fyfe et al., 2013; Lee et al., 2017; Mair et al., 1996) increasing two to three times the likelihood to suffer an identical injury (Hägglund et al., 2006). The persistence and/or exacerbation of one or more risk factors after rehabilitation and return to sport could explain the high prevalence of re-injury (J.-L. Croisier, 2004). However, despite the extensive literature about HSI, injury rates have not declined, in fact, it's rising (Jan Ekstrand et al., 2016). Therefore, accurate understanding of predisposing risk factor as well as maladaptation following the initial injury are necessary in order to design effective prevention and rehabilitation programs. However, for the purpose of this review point, the primary focus will be on muscular imbalance and fatigue.

2.4.2.1. Strength weakness and hamstrings to quadriceps ratio

A hamstrings to quadriceps ratio based on peak torque have been traditionally used as a measure of muscular imbalance, however, their predictive validity of HSI have contradictory findings, with several inconsistent results found in the literature. Given the hamstrings are exposed to higher degrees of strain during running (Mair et al., 1996), if the knee extensor are disproportionately stronger than their antagonists, the strain experienced by the knee flexors increases, resulting in higher injury risk. Initial investigations used the conventional hamstring to quadriceps ratio (H:Q) as a measure of risk injury to sustaining HSI (J.-L. Croisier, 2004), however the validity of the conventional H:Q ratio was rapidly questioned for ignoring the eccentric role of the hamstrings during running. Consequently, the functional H:Q has become accepted (J. L. Croisier et al., 2008; Yeung, Suen, & Yeung, 2009). In a large cohort prospective study by Van Dyk et al., (2016b) that analyzed the incidence of HSI based on different cut-offs of concentric and eccentric hamstring torques at $60^{o}.s^{-1}$ and $300^{o}.s^{-1}$, found no association between lower cut-offs and HSI suggesting that it’s a weak risk factor. However, J. L. Croisier et al., (2008), also in a prospective study found a significantly increased rate of injury in players with higher strength imbalances. In a recent review study by Dauty et al., (2018) the use of isokinetic strength cut-offs was misadvised as they analyzed different cut-offs, 0.60 and 0.47 for the conventional hamstring-to-quadriceps ratio and found no association with HSI incidence. Also, J.-L. Croisier, Forthomme, Namurois, Vanderthommen, & Crielaard, (2002) showed a preferential flexor eccentric weakness other than concentric weakness following a hamstring injury. These contradictory findings led to the conclusion that the isokinetic strength assessment for detecting the risk of future HSI was limited and lacks evidence (Green et al., 2018). One possible explanation to these inconsistent results could be the heterogeneous use of cut-off values used in different investigations (Grygorowicz et al., 2017).

However, some findings suggest that neuromuscular maladaptation can occur following HSI. A preferential eccentric hamstring weakness was found in previous studies between previously injured and uninjured limbs and/or athletes (J. Croisier, 2002; Opar et al., 2013). This contraction-mode preferential eccentric weakness, in previously injured hamstrings, is suggestive of neuromuscular inhibition (Fyfe et al., 2013). Additionally, Sole, Milosavljevic, Nicholson, & Sullivan, (2011) have found consistent lower myoelectric activity in previously injured hamstrings at long muscle lengths, suggesting possible that neural inhibition at long hamstring lengths could play an important role in the re-injury rates. Also, as previously stated, the majority of HSI affect the long head of the biceps femoris (Askling et al., 2007; Woods, 2004). Consequently, reports that used MRI to study the architectural changes following HSI found that prior injury led to significantly lower muscle volume of the biceps femoris long head, and, concomitantly, hypertrophy of the short head of the biceps femoris (Silder et al., 2008). This concomitant hypertrophy of the short head, and atrophy of the long head is also suggestive of chronic inhibition following strain injury (Fyfe et al., 2013). Also, recently, Opar et al. (2013) have shown a lower rate of torque and electromyographic development in previously strained hamstrings during anticipated eccentric contractions at $-60^{o}.s^{-1}$ at 50 and 100 ms.

These results suggest that neuromuscular function of the hamstrings should be looked with attention, specifically the early torque-time trace at long hamstring lengths.

2.4.2.2. The role of fatigue

Fatigue is commonly reported as potential risk factor of HSI (Fyfe et al., 2013; Mair et al., 1996; Woods, 2004). Fatigue can be defined as a temporary loss in the capacity for developing force of a muscle, which is reversible by rest (Gandevia, 2001). Fatigue can also be divided into central fatigue (failure to voluntary activate the muscles) and peripheral fatigue (when failure occurs near the neuromuscular junction) (Gandevia, 2001). Furthermore, fatigue will depend on exercise type and it’s intensity, the muscle groups involved and the environment in which is performed (Gandevia, 2001). Moreover, it has been proposed that fatigue may increase the injury susceptibility (Mair et al., 1996; Woods, 2004).

Early reports showed an increased incidence of HSI towards the final third of the first and second halves of the football match (Jan Ekstrand et al., 2011; Woods, 2004, Figure 2). This reports led to investigations on the effect of fatigue on several hamstring function parameters. Fatigue following intermittent running protocols found a predominantly decline in eccentric hamstring strength (Greig, 2008; Rahnama et al., 2003). Additionally, earlier reports, found higher knee extension angles during the late swing phase of high-speed over ground running in a fatigued condition (Pinniger et al., 2000). A possible explanation could be the reduced capability to activate the hamstrings following fatigue, which reduces the capacity of the muscle to generate contractile force, which limits the energy-absorbing of the musculotendinous unit (Mair et al., 1996) . In summary fatigue could play an important role in HSI as a higher degree of knee extension during the late swing phase of high-speed running can cause an over-lengthening of the hamstring muscles which may increase the susceptibility to injury. Furthermore, fatigue induced by intermittent running protocols were found to affect predominantly eccentric hamstring strength which is the primary hamstring function during the proposed mechanism of injury.

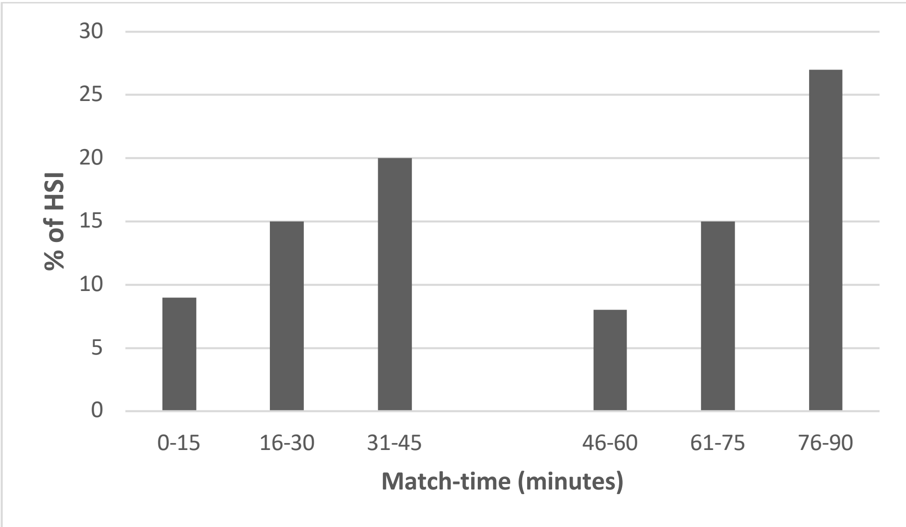

Figure 2: Time of hamstring strains during match play, adapted from Woods (2004).

2.5. Rate of force Development

As previously suggested, explosive-type movements such as high-speed running usually occur in 50-250 ms (Aagaard et al., 2002; Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2017). Therefore, the ability to rapidly activate the hamstrings relatively to the quadriceps at long hamstrings lengths is of paramount importance (Aagaard et al., 2002; Thelen et al., 2005). Secondary to, the time-wise nature of the proposed mechanism of injury (50-250 ms) and the time available to attain peak torque (~500 ms) suggests that discrepancy exists. As such, high rates of force development (or rate of torque development, RTD) are important characteristics of hamstring function because the limited time available for deceleration prevents the development of maximal torque.

Rate of force development is the ability to increase force or torque as quickly as possible during a rapid voluntary contraction realized from a low or resting level (Aagaard et al., 2002; Rodríguez-Rosell et al., 2016). It can be defined as the rate of rise in contractile force at the onset of contraction and is obtained from the slope of the torque-time curve (Δmoment/Δtime) (Aagaard et al., 2002). Therefore, the rate of force development has high functional significance in explosive-type movements where a fast and forceful muscle contraction is required (e.g. high-speed running). Since the short contraction time available in these actions may not allow for maximum force to be attained, any increase in contractile rate of force development, as it allows for a higher degree of muscle force in the early moments of contraction, would be beneficial (Aagaard et al., 2002; Maffiuletti et al., 2016). Additionally, rate of force development seems to be better correlated with functional sport tasks (Tillin, Pain, & Folland, 2013), detects changes in neuromuscular function (Angelozzi et al., 2012) and its underlying mechanism are different than those used to reach maximal force production (Andersen & Aagaard, 2006). Also, previous reports found that fatigue impairs differently in maximal voluntary contractions (MVC) and rate of force development (RFD) (Thorlund, Aagaard, & Madsen, 2009; Thorlund, Michalsik, Madsen, & Aagaard, 2008). Based on these aspects, Zebis et al. (2011) proposed the RTD H/Q to assess the knee joint muscle balance during explosive movements. Access the RTD H/Q at various time intervals (50-250ms) can be useful to study the ability of previously injured hamstrings muscles to overcome the fast and forceful contraction of the quadriceps muscles in explosive contractions, such as those found in high-speed running.

Chapter 3: Study 1

Rapid hamstrings to quadriceps ratio at long muscle lengths in football players with previous hamstring strain injury.

3.1. Abstract

Hamstring strain injuries (HSI) are extremely common in football and are the primary cause of re-injury in football players. Although the isokinetic strength ratios have often been used to predict hamstring injuries in football players, the rate of torque development hamstring to quadriceps ratio (RTD H/Q) has rarely been considered in previous reports. Furthermore, little consideration has been given to selective hamstring lengths and its influence on torque production. The aim of this study was to investigate the RTD H/Q at long hamstring lengths and the conventional (concentric/concentric) and functional (eccentric/concentric) hamstrings/quadriceps (H/Q) ratios in football players with and without previous HSI. Twenty-four professional men's football players (12 with and 12 without previous HSI) performed maximal voluntary isometric at long hamstring lengths (30º knee flexion) and isokinetic concentric and eccentric contractions at $180°.s^{-1}$ and $60°.s^{-1}$ of both quadriceps and hamstring muscles. Conventional and functional H/Q ratios based on peak torque throughout the entire isokinetic range of motion and at 30° of knee flexion were calculated. Long hamstring lengths RTD H/Q was extracted at incrementing time periods of 50 milliseconds (ms) from the onset of contraction (50-250 ms). No significant differences were found between players with and without HSI in any H/Q ratios studied. However, small effects (d=0.4) were found in previously injured hamstring to lower eccentric torque and RTD H/Q at 50 ms. Previous hamstring strain injury group showed small to moderate ($0.4>d<0.6$) higher rate of torque development ratios in late time intervals (>100 ms) as well.

Keywords: explosive strength, hamstring strain, professional football, hamstring strength

3.2. Introduction

Hamstring strain injuries (HSI) are still the most common muscle injury in a professional football setting, with a prevalence of 12% (Jan Ekstrand et al., 2011; Jan Ekstrand et al., 2011; Woods, 2004). Time lost and injury recurrence are also amongst the highest, even after rehabilitation programs, with a recurrence rate of 12-16% (Jan Ekstrand et al., 2012, 2011; Woods, 2004). An average of 5-7 HSI, accounting for a total of 82-90 days of absence and 15 matches missed per club, per season, should be expected in a squad of 25 players (Jan Ekstrand et al., 2011; Woods, 2004). There are several HSI risk factors reported in the literature, such as age (Freckleton & Pizzari, 2013; Fyfe et al., 2013; Opar et al., 2012), ethnicity (Fyfe et al., 2013), insufficient warm-up (Woods, 2004), poor flexibility (Fyfe et al., 2013; Woods, 2004), muscle imbalances (Lee et al., 2017; Woods, 2004), muscle weakness (Fyfe et al., 2013; Lee et al., 2017; Woods, 2004), neural tension (Woods, 2004) and fatigue (Fyfe et al., 2013; Woods, 2004). However, previous injury remains as the main risk factor (Arnason et al., 2004; Fyfe et al., 2013; Lee et al., 2017; Mair et al., 1996) increasing two to three times the likelihood to suffer an identical injury (Hägglund et al., 2006). High-speed running is often identified as the general mechanism of injury (Elliott et al., 2011a; Woods, 2004), with several studies suggesting the end of the swing phase as the most prone to injury due to the significant strain and rapid eccentric overloading placed on the hamstring muscles at long lengths (Heiderscheit et al., 2005; Thelen et al., 2005).

Factors leading to re-injury remain unknown, such as inadequate rehabilitation, premature return to play or possible maladaptation to injury are some of the proposed intrinsic risk factors (van Beijsterveldt, van de Port, Vereijken, & Backx, 2013). Therefore, an accurate understanding of possible maladaptation following HSI is required to achieve effective injury rehabilitation programs. A hamstring to quadriceps (H/Q) strength ratio based on peak torque during maximal isokinetic concentric and eccentric contractions has been extensively studied in either prospective (J. L. Croisier et al., 2008; Dauty, Menu, & Fouasson-Chailloux, 2018; Lee et al., 2017; Van Dyk et al., 2016b) and retrospective (Lord et al., 2018) studies to describe its relation to HSI with conflicting results. Nevertheless, the deceleration of the advancing thigh during the late swing phase of high-speed running (Thelen et al., 2005), usually occurs in less than 250 milliseconds (ms) (Aagaard et al., 2002; Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2017). Moreover, during this stage, the hip is flexed and the knee is extending leading to the peak of hamstring muscle-tendon length (Heiderscheit et al., 2005; Thelen et al., 2005). Therefore, the ability to rapidly activate the hamstrings relatively to the quadriceps at long hamstrings lengths is of paramount importance (Aagaard et al., 2002; Thelen et al., 2005). Zebis et al., (2011) have recently introduced a rate of torque development (RTD) H/Q ratio (RTD H/Q) to assess the ability of knee joint muscles to stabilize the knee during explosive movements. Despite this, the relationship between HSI and deficits of RTD and RTD H/Q hamstrings at long muscle lengths has rarely been considered. Recently, Opar et al., (2013) have shown a lower rate of torque and electromyographic development in previously strained hamstrings during anticipated eccentric contractions at -60º.s^{-1} at 50 and 100 ms. Also, Sole et al., (2011) have found consistent lower myoelectric activity in previously injured hamstrings at long muscle lengths, suggesting possible neural maladaptation can occur at long hamstrings lengths. These results set the basis for further studies on possible RTD maladaptation, at various time intervals, at long muscle lengths to previous HSI. Also, it suggests that discrepancy exists in the time-wise nature of peak torque H/Q ratio and the time available to produce force during high-speed running. Access the RTD H/Q at various time intervals (50-250 ms) can be useful to study the ability of previously injured hamstrings muscles to overcome the fast and forceful contraction of the quadriceps muscles in explosive contractions, such as those found in high-speed running. Besides that, the sensitivity of RTD may give us the ability to detect changes in neuromuscular function (Jenkins et al., 2014; Peñailillo, Blazevich, Numazawa, & Nosaka, 2015). Given that, the main purpose of this study was to investigate the RTD and RTD H/Q at long hamstring lengths (i.e., 30° knee joint flexion) and the conventional (concentric/concentric) and functional (eccentric/concentric) H/Q ratios among professional football players with and without previously injured hamstrings. We hypothesized that previously strained hamstrings had 1) lower RTD and RTD H/Q ratios at long muscle lengths, a 2) lower concentric and eccentric peak torques, and 3) lower conventional and functional H/Q ratios.

3.3. Materials and Methods

<u>Subjects</u>

This study is a case-control study with 24 (twenty-four) male professional football players (Table 1) competing in several teams of the 1st and 2nd Portuguese National Leagues, who volunteered to take part in this study. All tests were conducted during mid-season. The subjects were assigned to either a previously injured (PI, n=12) or uninjured group (UG, n=12) based on the following criteria (Lord et al., 2018), determined by an injury questionnaire: 1) at least one previous HSI of the dominant leg (referred to as the preferred kicking leg) clinically diagnosed by the team medical department; 2) the injury caused at least one week of missed practice; 3) the injury occurred within the last 24 months; 4) currently injury free and competing and 5) familiar with the extension-flexion isokinetic testing of the knee. Written informed consent was read and signed by all participants. The study was conducted according to the Declaration of Helsinki, with approval from the local ethical committee (CEFMH:13/2018).

Table 1: Age, height, weight and body mass index (BMI) from the uninjured group (UG) and the previous injury group (PI).

	UG (n=12)	PI (n=12)
Age (y)	22.6 ± 3.1	26.5 ± 5.4 *
Height (m)	182.2 ± 6.7	178.8 ± 7.0
Weight (kg)	76.7 ± 8.5	74.4 ± 6.8
BMI ($kg.m^{-2}$)	23.1 ± 1.8	23.3 ± 1.2

Values are means ± SD; * $P < 0.05$; significantly different from UG group.

Injury Questionnaire

All participants completed an injury questionnaire under the guidance of their chosen physician /physiotherapist, in which the date of injury, return to training and competition, severity (grade I, II or III) (Blankenbaker & Tuite, 2010), limb (dominant or non-dominant) and location of the injury (biceps femoris long head, biceps femoris short head, semitendinosus, semimembranosus) were reported.

Isokinetic and Isometric Testing

Isokinetic and isometric strength tests were performed for the dominant leg using an isokinetic dynamometer (System 3; Biodex Medical Systems, Shirley, NY). Participants were seated on dynamometer chair with their hip positioned at 85º (supine position=0°) and strapped around their chest, hip and distal thigh to minimize extraneous movement. The knee center of rotation was carefully aligned with the dynamometer axis of rotation, and the lever arm of the dynamometer was firmly attached to the lower leg with inextensible straps 2cm above the medial malleolus. The knee range of motion was set to

90° (0° of extension to 90° of flexion) for the isokinetic measurements and fixed at a static position of 30° of knee flexion for the isometric trials. This last knee joint position corresponding to long hamstring length was selected because it is a position where peak hamstring elongation happens in high-speed running, specifically in the late swing phase (Thelen et al., 2005).

Maximum concentric contractions for both hamstrings (HAMS) and quadriceps (QUAD) were performed at 180º.s^{-1} (5 reps) and 60º.s^{-1} (4 reps) separated by a rest period of 90 seconds. Additionally, eccentric contractions of HAMS (4 reps) were also performed at 60º.s^{-1} and 180º.s^{-1} during which the isokinetic dynamometer was set to work under the passive mode. Then, 4 maximal voluntary isometric contractions (MVIC) were recorded for both HAMS and QUAD with 30 seconds between trials. Isometric trials were alternated between HAMS and QUAD to prevent fatigue. To ensure an accurate assessment of maximal isokinetic and isometric strength, online visual feedback of the instantaneous dynamometer torque was provided to the subjects on a computer screen. Instructions were given to the subjects to perform all contractions as fast and forceful as possible to obtain both maximal torque and RTD. Trials with visible initial countermovement were excluded and a subsequent trial was added. The torque signals were A/D converted (MP100 – Biopac™ Systems, 16-bits) with a sample rate of 1000 Hz and low-pass filtered at 12Hz (zero phase shift 4th order Butterworth filter) using a custom-built routine for analysis (MATLAB version R2014b). All recorded torques were corrected for the effect of gravity on the lower limb (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1995). Measurements were preceded by a controlled 5-minute cycle ergometer (Monark Exercise AB, Sweden) warm-up (100 watts at 80 rpm), followed by 5 submaximal contractions at an increasing intensity and 2 maximal contractions trials at 180º.s^{-1}.

Conventional and Functional H/Q ratios

Trials with the highest concentric and eccentric peak torque at both angular velocities were selected for analysis. The conventional H/Q ratio was calculated as the HAMS concentric peak torque divided by the QUAD concentric peak torque at both angular velocities and for MVIC ($H_{conc180}/Q_{conc180}$, H_{conc60}/Q_{conc60}, H_{MVIC}/Q_{MVIC}). The functional H/Q ratio was determined as the HAMS eccentric peak torque divided by the QUAD concentric peak torque ($H_{ecc180}/Q_{conc180}$, H_{ecc60}/Q_{conc60}). Also, the QUAD and HAMS isokinetic torques in a pre-selected knee joint flexion of 30º were selected for analysis and used to calculate the conventional ($H_{con180}/Q_{conc180}$ @30º, H_{con60}/Q_{conc60} @30º) and the functional H/Q ratios ($H_{ecc180}/Q_{conc180}$ @30º, H_{ecc60}/Q_{conc60} @30º) at long hamstring lengths.

Rate of Torque Development H/Q ratios

Rate of torque development (Nm/ms) for both QUAD and HAMS MVIC was calculated as the slope of the torque-time curve (i.e., Δtorque/Δtime) in incremental time periods of 50 ms starting from the onset of contraction, over five distinct time intervals (i.e., 0–50, 0–100, 0–150, 0–200 and 0-250 ms). The onset of force production was set as the time point where the torque exceeded baseline by 3 N.m (Aagaard et al., 2002; Maffiuletti et al., 2016; Opar et al., 2013) for both QUAD and HAMS muscles. The maximum torque-time slope at time windows of 20 ms (Rodríguez-Rosell et al., 2017), was then calculated to determine the peak rate of torque development (pRTD). The RTD H/Q ratios were calculated as described elsewhere (Zebis et al., 2011), by dividing the HAMS RTD by the QUAD RTD into the corresponding time intervals (for example RTD H_{0-50}/Q_{0-50}) (Zebis et al., 2011).

3.4. Statistical Analysis

Data are presented as means ± standard deviations (SD) unless stated otherwise. Independent samples t-tests were performed between groups to assess whether significant differences existed between the previously injured and uninjured groups at a significance of $P<0.05$. When data did not meet the criterion of normal distribution, Wilcoxon signed-rank test was performed. Cohen's *d* effect-size analysis was used to examine the magnitude of differences between groups. Threshold values of 0.2, 0.5 and 0.8 were used to represent small, moderate and large effects, respectively (Lakens, 2013). All data were analyzed using IBM SPSS Statistics (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp.).

3.5. Results

Subjects

Both UG and PI groups were similar in body mass, height and body mass index (see table 1). However, significant differences were found with respect to age (UG: = 22.6 ± 3.1 years vs PI = 26.6 ± 5.4 years, P=0.05, d=0.9). From the injured group, 66% of the injuries were located to the Biceps Femoris long head, whereas the other 33% were located at the medial hamstrings. Mean time since last injury was 10 months (range: 2-24 months) and mean time absent from practice was 5 weeks (range: 2-16 weeks).

Isokinetic and Isometric Strength

No significant differences were found between groups for both QUAD and HAMS peak torque at any angular velocity considered ($P > 0.05$, Table 2). Also, no differences were found between groups for both QUAD and HAMS isokinetic torque at 30° of knee flexion ($P > 0.05$). Relatively to isometric data, no significant differences between UG and PI groups were found for both QUAD and HAMS isometric strength and RTD (Table 2).

Table 2: Quadriceps (QUAD) and Hamstrings (HAMS) isometric and isokinetic data. Isokinetic Strength: concentric (CONC) and eccentric (ECC) peak torque, angle of peak torque and peak torque at 30º of knee flexion (@30º). Isometric Strength: maximal voluntary isometric contraction (MVIC) and peak rate of torque development (pRTD).

		UG (n=12)	PI (n=12)	ES (*d*)
Isokinetic Strength				
Peak Torque (N▪m)				
QUAD CONC	180°.s^{-1}	154.9 ± 12.7	158.6 ± 26.4	0.2
	60°.s^{-1}	223.4 ± 25.6	223.7 ± 39.6	0.0
HAMS CONC	180°.s^{-1}	92.4 ± 15.8	98.89 ± 13.2	0.4
	60°.s^{-1}	123.1 ± 26.5	128.8 ± 21.1	0.2
HAMS ECC	180°.s^{-1}	175.3 ± 54.9	170.6 ± 38.6^{c}	0.2
	60°.s^{-1}	161.8 ± 50.8	167.5 ± 38.9	0.1
Angle of Peak Torque (°)				
QUAD CONC	180°.s^{-1}	59.6 ± 5.5	59.2 ± 9.3	0.1
	60°.s^{-1}	64.9 ± 5.4	65.5 ± 8.5	0.1
HAMS CONC	180°.s^{-1}	36.3 ± 12.4	32.7 ± 10.9	0.3
	60°.s^{-1}	23.4 ± 8.1	25.4 ± 5.7^{c}	0.3
HAMS ECC	180°.s^{-1}	19.4 ± 10.8	16.4 ± 8.9	0.3
	60°.s^{-1}	18.1 ± 13.2	17.1 ± 9.8^{c}	0.1
Peak Torque @30º (N▪m)				
QUAD CONC	180°.s^{-1}	108.5 ± 13.9	109.3 ± 23.6	0.0
	60°.s^{-1}	117.3 ± 25.3	114.2 ± 32.6	0.1
HAMS CONC	180°.s^{-1}	77.4 ± 17.9	85.6 ± 12.8	0.5
	60°.s^{-1}	99.3 ± 29.7	106.8 ± 28.9	0.3
HAMS ECC	180°.s^{-1}	137.4 ± 46.9	135.75 ± 22.8	0.1
	60°.s^{-1}	137.3 ± 48.8	135.9 ± 32.0	0.0

Table 2 continuance

Isometric Strength

Maximal Voluntary Isometric Contraction (N▪m)				
	QUAD MVIC	156.2 ± 24.5	152.7 ± 42.6	0.1
	HAMS MVIC	122.3 ± 39.4	121.9 ± 22.4	0.0
Rate of Torque Development (N▪m/ms)				
	QUAD pRFD	0.93 ± 0.36	1.03 ± 0.48	0.2
	HAMS pRFD	0.72 ± 0.39	0.72 ± 0.29	0.0

[c] Wilcoxon Mann-Whitney signed-rank test was performed;

<u>*Conventional, Functional and RTD H/Q Ratios*</u>

No significant differences were found between groups for both conventional and functional H/Q ratios (P > 0.05, Table 3), although small to moderate effects were found for some conventional H/Q ratios, with the previously injured population showing a small effect towards a greater knee muscle balance when the peak torque was considered: $H_{conc180}/Q_{conc180}$ (UG: 0.60 ± 0.09 vs PI: 0.63 ± 0.07, P=0.319, d=0.4), $H_{conc180}/Q_{conc180}$ at 30º of knee flexion (UG: 0.72 ± 0.18 vs PI: 0.82 ± 0.20, P=0.219, d=0.5), H_{conc60}/Q_{conc60} (UG: 0.55 ± 0.12 vs PI: 0.59 ± 0.12, P=0.800, d=0.4) and H_{conc60}/Q_{conc60} at 30º of knee flexion (UG: 0.85 ± 0.19 vs PI: 1.05 ± 0.64, P=0.544, d= 0.4).

However, the RTD H/Q ratios showed that the previously injured population presented a small effect with no statistical significance (P > 0.05, d >0.2) for lower RTD H/Q ratios in the very initial phase of muscle contraction: RTD H_{50}/Q_{50} (UG: 1.69 ± 0.66 vs PI: 1.43 ± 0.73, P=0.383, d= 0.4) and higher later RTD H/Q ratios: RTD H_{150}/Q_{150} (UG: 0.73 ± 0.25 VS PI: 0.83 ± 0.25, P=0.357, d=0.4), RTD H_{200}/Q_{200} (UG: 0.72 ± 0.22 vs PI: 0.85 ± 0.25, P=0.200, d=0.6) and RTD H_{250}/Q_{250} (UG: 0.72 ± 0.24 vs PI: 0.84 ± 0.26, P=0.271, d=0.5) (See table 3 and figure 3).

Table 3: Hamstring-to-Quadriceps Ratios (H//Q ratios): Conventional and Functional H/Q ratios based on peak torque and at 30º of knee flexion and RTD H/Q ratios based on incremental time periods of 50 ms.

			UG (n=12)	PI (n=12)	ES (*d*)
H/Q Isokinetic Ratios					
Conventional (HAMSconc:QUADconc)	Based on Peak Torque	180°.s^{-1}	0.60 ± 0.09	0.63 ± 0.07	0.4
		60°.s^{-1}	0.55 ± 0.12	0.59 ± 0.12	0.4
	@30º	180°.s^{-1}	0.72 ± 0.18	0.82 ± 0.20	0.5
		60°.s^{-1}	0.85 ± 0.19	1.05 ± 0.64	0.4
Functional (HAMSecc:QUADconc)	Based on Peak Torque	180°.s^{-1}	1.13 ± 0.33	1.10 ± 0.29	0.1
		60°.s^{-1}	0.73 ± 0.22	0.76 ± 0.17	0.2
	@30º	180°.s^{-1}	1.29 ± 0.48	1.29 ± 0.31	0.0
		60°.s^{-1}	1.20 ± 0.42	1.32 ± 0.68	0.2
H/Q Isometric Ratio					
Based on Peak Torque @30º			0.78 ± 0.22	0.85 ± 0.26	0.3
H/Q RTD Ratios					
Based on incremental time periods of 50 ms		H/Q 50	1.69 ± 0.66	1.43 ± 0.73	0.4
		H/Q 100	0.94 ± 0.35	0.93 ± 0.38	0.0
		H/Q 150	0.73 ± 0.25	0.83 ± 0.25	0.4
		H/Q 200	0.72 ± 0.22	0.85 ± 0.25	0.6
		H/Q 250	0.72 ± 0.24	0.84 ± 0.26	0.5

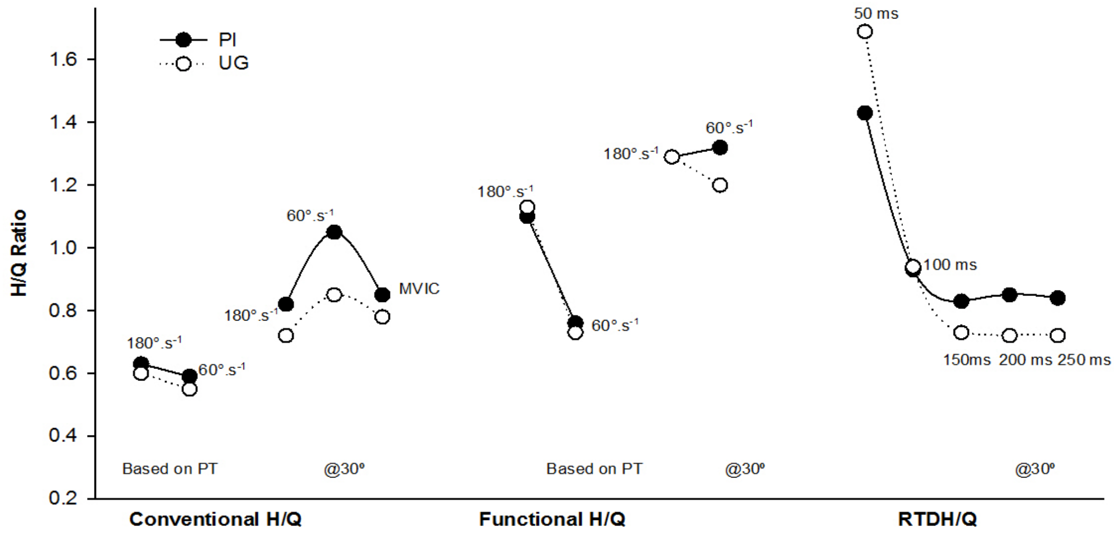

Figure 3: Hamstring-to-Quadriceps Ratios (H//Q ratios): Conventional and Functional H/Q ratios based on peak torque and at 30º of knee flexion and RTD H/Q ratios based on incremental time periods of 50 ms.

3.6. Discussion

The biarticular hamstring muscles are the most commonly strained muscles in professional football players (Jan Ekstrand et al., 2011; Jan Ekstrand et al., 2011; Woods, 2004). The need for rapid deceleration of the advancing thigh during late swing phase of high-speed running (Thelen et al., 2005) forces the hamstrings muscles to a significant amount of strain at long muscle lengths in a short time window. Given this, the rate of force development (or RTD as we have studied) is the key of hamstring function. As the lower RTD could have important implications for hamstring strain injury or re-injury (Opar et al., 2013), the main purpose of this study was to investigate the RTD H/Q at long hamstring lengths and the conventional and functional H/Q ratios in professional football players with (PI) and without (UG) previously injured hamstrings.

Before discussing the main findings of our study, we would like to note that the PI subjects were significantly older than the UG. This result is in agreement with previous prospective studies that found previous injury and age as a significant injury risk factor

(Henderson, Barnes, & Portas, 2010; van Beijsterveldt et al., 2013; Woods, 2004). However, it should be noted that no other demographic differences were found between groups, which is also in accordance with literature (van Beijsterveldt et al., 2013).

Rate of force development is a sensitive measure to muscle damage when evaluated isometrically (Angelozzi et al., 2012). It's also highly correlated with functional tasks of sport and depends on neural mechanisms (Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2017). Given the reduced time available to perform explosive movements such as sprinting (50-250 ms), maximal muscle strength, which is reached in approximately 500 ms from onset of contraction (Aagaard et al., 2002), may not be attained. With this in mind, we hypothesized that RTD H/Q ratios would be lower in previously injured hamstrings at various time intervals. The RTD H/Q ratio was first presented by Zebis et al., (2011) in elite football players with no previous history of HSI has shown that the method (i.e., H/Q ratio based on RTD during maximal voluntary static contraction) is relevant for the clinical evaluation of the agonist-antagonist relationship of the knee joint. Another study, also with professional football players with no known history of HSI but with heterogeneous values of conventional H/Q ratio, showed that players with high (0.66-0.70) and low (0.50-0.54) conventional H/Q ratios (Hcon:Qcon) tend to demonstrate similar profiles (i.e., high and low, respectively) in the RTD H/Q ratio (Greco, da Silva, Camarda, & Denadai, 2012). To the best of our knowledge, this is the first time that the RTD H/Q ratios were analyzed in professional football players with previous HSI as originally described. Opar et al., (2013) showed a lower rate of force development capabilities in football players with previous HSI, although it was measured in an eccentric contraction. In our study, we used isometric contractions because it's more reliable (Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2016), albeit less correlated with functional sports tasks. Contrary to our initial hypothesis, the PI group did not show any significant lower RTD H/Q ratios at different time periods (P>0.05), but showed a small effect towards a lower RTD H_{50}/Q_{50} (d=4) than the UG. These results are similar with the ones reported by Zebis et al., (2011) in which two athletes with markedly lower RTD H_{50}/Q_{50} ratio (~40%), but without any lowered H/Q ratio based on peak torque, were injured following one year after the study. As this time interval (50 ms) is within the early torque-time trace (<75 ms) we can assume that neural factors play a preponderant role and that the lower results found in this time frame can be explained by some neural inhibition at early contraction. Also, the later RTD H/Q ratios (>100 ms) showed an inversed scenario in which the PI showed small to moderate higher RTD H/Q ratios (d=0.4, d=0.6 and d=0.5 respectively for H_{150}/Q_{150}, H_{200}/Q_{200} and H_{250}/Q_{250}). The ability to produce force at the onset of a ballistic contraction, measured in an isometric contraction, and during the early phase of the torque-time trace (<75 ms) is more dependent of neural factors such as motor unit (MU) discharge rate, doublet discharges, lowered MU recruitment thresholds and increased spinal excitability (Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2017). However, the later phase of the torque-time trace (>75 ms) is more correlated with MVIC and the speed related properties of the muscle as its fiber composition and inherent cross-bridge cycle and Ca^{2+} release (Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2017). This supports our previous theory that some sort of neural inhibition following HSI persists long after rehabilitation and return to sport, which the reduces the ability to rapidly activate the hamstring muscles at long muscle lengths.

Hamstrings to quadriceps ratio based on peak torque have been traditionally used as a measure of muscular imbalance, however, their predictive validity of HSI have contradictory findings, with several inconsistent results found in the literature. A prospective study by Van Dyk et al., (2016) analyzed the incidence of HSI based on different cut-offs of conventional ratios at 60º.s^{-1} and 300º.s^{-1} having found no association between lower cut-offs and HSI. However, Croisier et al., (2008), also in a prospective study, found a significantly increased rate of injury in players with higher strength imbalances (J. L. Croisier et al., 2008). Also, Croisier et al., (2002) showed a preferential flexor eccentric weakness other than concentric weakness following a hamstring injury (J.-L. Croisier, Forthhomme, Namurois, Vanderthommen, & Crielaard, 2002). In fact, our results showed that previously injured players exhibited a small effect towards a reduced eccentric flexor peak torque at 180º.s^{-1} (UG: 175.3 ± 54.9 vs PI: 170.6 ± 38.6, *d*=0.2, table 2) and a slightly lower functional ratio at the same angular velocity (UG: 1.13 ± 0.33 vs PI:1.10 ± 0.29, *d*=0.1, table 3). This preferential eccentric hamstring weakness at 180º.s^{-1} (UG: 175.3 ± 54.9 vs PI: 170.6 ± 38.6, *d*=0.3) could be explained by some sort of neuromuscular inhibition. This explanation is supported by the study of Sole et al., (2011) who found a selective inability to activate the hamstring at long hamstring lengths. This can be caused by pain or neural inhibition, which reduces the adaptation to training at long hamstring lengths, potentially reducing the sarcomerogenesis, that furthers withdraws the adaptation to the stimulus of eccentric exercise and the benefits associated with this (Fyfe et al., 2013). Subsequently, a shift in the torque-angle relationship to longer optimum hamstring lengths is expected (Fyfe et al., 2013), which is in accordance to our findings that showed a significant higher knee flexion angle in the PI at a concentric isokinetic velocity of 60º.s^{-1} (UG: 23.4 ± 8.1 vs PI: 25.4 ± 5.7, *d*=0.3). Also, if we consider conventional H/Q cut-off values of 60% for an angular velocity of 60º.s^{-1} (UG: 0.55 ± 0.12 vs PI: 0.59 ± 0.12), 70% for 180º.s^{-1} (UG: 0.60 ± 0.09 vs PI: 0.63 ± 0.07, *d*=0.4) and 100-140% for the functional ratio (values at 60°.s^{-1}: UG: 0.73 ± 0.22 vs PI: 0.76 ± 0.17, *d*=0.2) (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998) neither the UG or the PI group meet the criteria which can also explain the lack of statistical significance found in our study. Another explanation could be that this elite population had access to comprehensive rehabilitation, more likely than semi-professional or amateur athletes, which can explain the non-significant measures between groups found in our study and the contradictory findings in previous studies. In conclusion, this moderate lower early contraction (<100 ms) RTD H/Q ratio found in the PI group could be caused as a maladaptation to injury, however future prospective studies should seek to find if players with lower early RTD H/Q ratio are more prone to injury as these results only tell us that moderate lower levels are found in players with previous injury.

3.7. Perspective

This was the first study to examine RTD H/Q in professional football players with previously injured hamstrings. Our results did not show significant differences between groups, however a small effect towards lower peak eccentric flexor torque, functional. Also, an RTD H/Q at very initial phase of contraction (50 ms) set the basis for future studies to measure neuromuscular capabilities in previously injured hamstring players with different methodologies, as electrically evoked stimulation. As fatigue is also a major injury risk factor, and RTD sensible to fatigue, future studies should see if RTD capabilities are altered following fatigue in previously injured hamstrings. Also, prospective studies should seek to investigate whether previous RTD H/Q are present in football players that sustain an HSI or if it is a maladaptation following injury.

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Chapter 4: Study 2

Acute fatigue-induced changes in rapid hamstrings to quadriceps ratio at long muscle lengths in professional football players with previous hamstring strain injury

4.1. Abstract

The aim of this study was to investigate the effect of fatigue induced by a laboratory-based football specific protocol on different hamstrings to quadriceps (H:Q) ratios in professional football players with previous hamstring strain injury (HSI). Twenty-four male professional soccer players (12 with and 12 without previous HSI) performed maximal concentric (conc) and eccentric (ecc) contractions at 180°.s^{-1} and 60°.s^{-1}. Conventional (H_{conc}/Q_{conc}) and functional (H_{ecc}/Q_{conc}) ratios were calculated based on peak torque as well as peak torque at 30º knee flexion. Additionally, maximal isometric voluntary contractions were performed at 30º knee flexion, where maximal voluntary isometric contraction (MVIC), peak rate of torque development and rate of torque development (RTD) were obtained to calculate the rapid hamstring to quadriceps (RTD H/Q) at incremental time periods of 50 milliseconds (ms). Significant differences were found between players with and without HSI in RTD H_{50}/Q_{50} ratio (p=0.02, d=1.0). Previous hamstring strain injury group showed small to moderate (0.3>d<0.6) lower rate of torque development ratios following fatigue in early time intervals (<150 ms) as well.

Keywords: muscle strain, peak hamstring length, fatigue, isometric, eccentric, concentric, rate of torque development, rate of force development

4.2. Introduction

Hamstring strain injuries (HSI) are the most common muscle injury in sports involving high speed running. In professional football, approximately 5-7 HSI, per season, are expected, in a squad of 25 players, with a recurrence rate of 12-16% (Jan Ekstrand et al., 2012, 2011; Woods, 2004). A total of 82-90 days of absence and 15 matches missed per club, per season, should be expected (Jan Ekstrand et al., 2011; Woods, 2004), which not only diminishes performance but also increases financial consequences for elite sports organizations. There are several HSI risk factors reported in the literature. Some of the proposed risk factors are non-modifiable, such as age (Freckleton & Pizzari, 2013; Fyfe et al., 2013; Opar et al., 2012), ethnicity (Fyfe et al., 2013) and previous injury (Arnason et al., 2004; Fyfe et al., 2013; Mair et al., 1996; Woods, 2004). Also, a number of modifiable risk factors, such as insufficient warm-up (Woods, 2004), poor flexibility (Fyfe et al., 2013; Woods, 2004), muscle imbalances (Lee et al., 2017; Woods, 2004), muscle weakness (Fyfe et al., 2013; Lee et al., 2017; Woods, 2004), neural tension (Woods, 2004) and fatigue (Fyfe et al., 2013; Woods, 2004) are reported. However, despite the extensive literature about HSI, injury rates have not declined, in fact, it's rising (Jan Ekstrand et al., 2016). This could be explained by the fact that, although HSI often occurs during high-speed running, research is mainly focused on evaluating maximal strength, which isn't achieved during high-speed running, as well as a non-running-specific range of motion. Therefore, focus should turn to modifiable risk factors, which can be targeted through an appropriate understanding of the mechanisms of injury, as well as maladaptation following injury.

Muscle strain injuries occur when the muscles fibers cannot withstand the excessive tensile forces placed upon them, this is usually associated to an eccentric contraction when a rapid acceleration/deceleration is required from a muscle in a lengthened position (Kujala, Orava, & Jiirvinen, 1997; Roig & Ranson, 2007). Therefore, it has been argued that HSI usually occur during high speed running (Elliott et al., 2011b; Woods, 2004), with the end swing phase as the most prone to injury due to the excessive rapid eccentric strain placed upon the hamstrings at the peak muscle lengths (Heiderscheit et al., 2005; Thelen et al., 2005; Yu et al., 2008). Recently, Sole et al., (2011) found that players with previous HSI have lower hamstrings myoelectrical activity at long muscle lengths, suggesting possible neural inhibition at long hamstrings lengths. Nevertheless, the deceleration of the advancing thigh during the late swing phase of high-speed running (Thelen et al., 2005), usually occurs in less than 250 milliseconds (ms) (Aagaard et al., 2002; Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2017). Furthermore, fatigue is perpetuated as an important risk factor, as previous reports have found an increased incidence of hamstring strain injuries towards the end of each half of a football match (Woods, 2004). Therefore, it is hypothesized that fatigue might impair muscle function, and increase the susceptibility to injury. However, traditionally, muscular imbalance and fatigue have been evaluated through conventional and functional hamstrings to quadriceps ratio based on peak torque values (J. L. Croisier et al., 2008; Lord et al., 2018). However, peak torque occurs about 500 ms after the onset of contraction while explosive movements, such as high-speed running, occurs in ~50-250 ms (Aagaard et al., 2002). Thus, assess knee muscle balance based on peak torque values do not reflect the time-wise nature of the proposed mechanism of injury (i.e. high-speed running). Nonetheless, few have explored the rapid force capabilities of the hamstrings muscles when studying HSI (Opar et al., 2013), as well as the influence of fatigue in explosive strength (Thorlund et al., 2009). Thorlund et al., (2009, 2008) have shown that fatigue impairs differently muscle maximal voluntary contraction

(MVC) and the rate of force development (RFD). These results suggest that different mechanisms are responsible for attaining maximal strength and the ability to rapidly activate the muscles. However, few have explored the rapid hamstrings to quadriceps ratio (Greco et al., 2012; Zebis et al., 2011) in previously injured hamstrings at long muscle lengths, as well as their rapid force capacities in a fatigued state (Greco, Da Silva, Camarda, & Denadai, 2013). Given this, and based on the time-wise nature of explosive-type movements, we proposed the rate of torque development (RTD) hamstrings to quadriceps ratio (RTD H/Q), at different time intervals (Zebis et al., 2011), to study the effects of fatigue on previously injured hamstrings. Given that, the main purpose of this study was to investigate the effect of fatigue induced by a laboratory-based specific fatigue protocol (FAST-FP) (Cortes, Greska, Kollock, Ambegaonkar, & Onate, 2013) on RTD and RTD H/Q at long hamstring lengths and the conventional (concentric/concentric) and functional (eccentric/concentric) H/Q ratios among professional football players with previously injured hamstrings. We hypothesized that players with previously injured hamstrings had 1) greater fatigue impaired of the RTD H/Q ratios at long muscle lengths, 2) a lower concentric and eccentric peak torques after fatigue, and 3) lower conventional and functional H/Q ratios.

4.3. Materials and methods

Study design

To investigate the hypothesis of the present study, a case-control experimental design was used to investigate the effect of fatigue on the knee muscle balance at long hamstring lengths of football players with previous HSI. After completed an injury questionnaire under the guidance of their chosen physician /physiotherapist, twenty-four male professional football players were assigned to either a previously injured (PI, n=12) or a control uninjured group (UG, n=12), based on the following criteria (Lord et al., 2018): 1) at least one previous HSI of the dominant leg (referred to as the preferred kicking leg) clinically diagnosed by the team medical department; 2) the injury caused at least one week of missed practice; 3) the injury occurred within the last 24 months; 4) currently injury free and competing and 5) familiar with the extension-flexion isokinetic testing of the knee.

Isokinetic and isometric strength for both quadriceps and hamstrings muscles were assessed before (Pre) and 3 minutes after (Post) the functional agility short term fatigue protocol (FAST-FP), seeking to mimic the loads and characteristics of team sports (Figure 4). The knee muscle balance was determined through H/Q ratios calculated based on isokinetic peak torque, isokinetic torque @30°, and both isometric peak torque and RTD at 30º of knee flexion. Measurements were preceded by a controlled 5-minute cycle ergometer (Monark Exercise AB, Sweden) warm-up (100 watts at 80 rpm), followed by 5 submaximal contractions at an increasing intensity and 2 maximal contractions trials at 180º.s^{-1}. During all tests, players were allowed to drink water *ad libitum*.

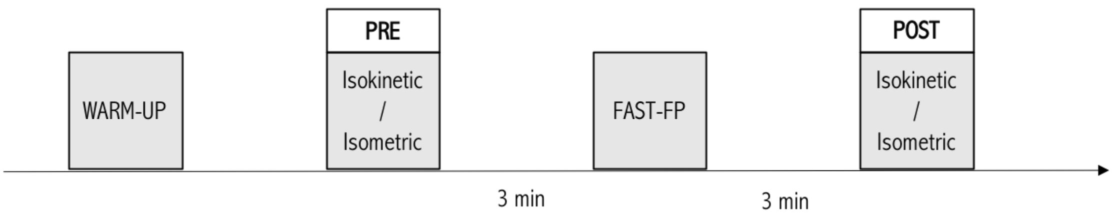

Figure 4: Overview of the protocol of the Pre and Post test with the fatigue protocol (FAST-FP). Pre and Post tests were separated from the FAST-FP with 3 minutes.

Subjects

Twenty-four male professional football players, playing in the 1st and 2nd Portuguese National Leagues, participated voluntarily in this study. Players were assigned to either a previously injured (PI; n=12; age, 26.5 ± 5.4 years; height, 1.79 ± 0.07 m, body mass, 74.4 ± 6.8 kg; means ± SD) or a control uninjured group (UG; n=12; age, 22.6 ± 3.1 years; height, 1.82 ± 0.07 m, body mass, 76.7 ± 8.5 kg; means ± SD).

All subjects were informed of the benefits and potential risks of the investigation prior to signing an institutionally approved informed consent to participate in the study. All procedures were approved by the local Ethical Board and were consistent with requirements for human experimentation (CEFMH:13/2018).

Functional agility short term fatigue protocol (FAST-FP)

The FAST-FP (Figure 5) was completed in accordance with previous studies (Cortes, Quammen, Lucci, Greska, & Onate, 2012; Wilke, Fleckenstein, Krause, Vogt, & Banzer, 2016), which consists in repeated sets of four consecutive components: 1) three consecutive countermovement jumps (CMJ), 2) a 20-s bout of step ups on a 32-cm box at a frequency of 220 beats/minute, 3) three bodyweight squats and 4) an agility run (5-10-5 drill). These sets were repeated until the participants no longer achieved 90% of their maximum CMJ height in two consecutive sets. Verbal encouragement was given to all subjects throughout the protocol.

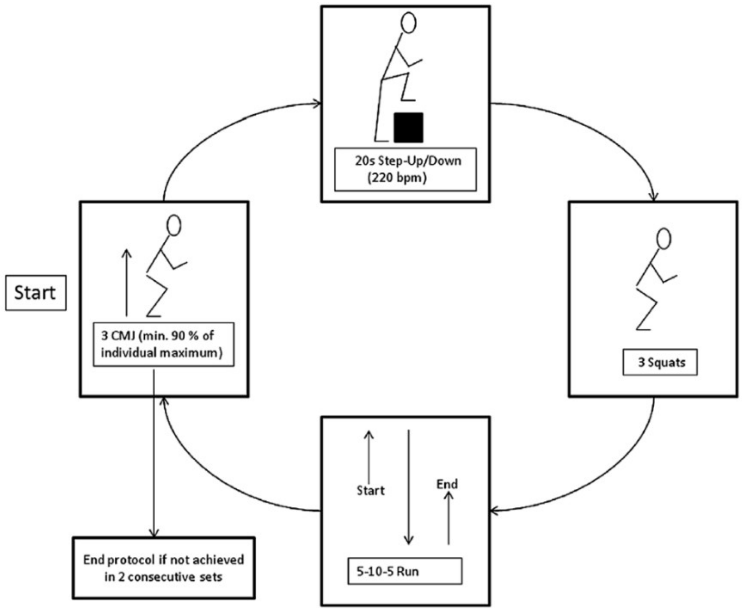

Figure 5: The components of the FAST-FP, retired from Wilke et al., (2016).

<u>Isokinetic and Isometric Testing</u>

Isokinetic and isometric strength tests were performed for the dominant leg using an isokinetic dynamometer (System 3; Biodex Medical Systems, Shirley, NY). Participants were seated on dynamometer chair with their hip positioned at 85º (supine position=0°) and strapped around their chest, hip and distal thigh to minimize extraneous movement. The knee center of rotation was carefully aligned with the dynamometer axis of rotation, and the lever arm of the dynamometer was firmly attached to the lower leg with inextensible straps 2cm above the medial malleolus. The knee range of motion was set to 90° (0° of extension to 90° of flexion) for the isokinetic measurements and fixed at a static position of 30° of knee flexion for the isometric trials. This last knee joint position, corresponding to long hamstring length, was selected because it is a position where peak hamstring elongation happens in high-speed running, specifically in the late swing phase (Thelen et al., 2005).

Maximum concentric contractions for both hamstrings (HAMS) and quadriceps (QUAD) were performed at 180º.s^{-1} (5 reps) and 60º.s^{-1} (4 reps) separated by a rest period of 90 seconds. Additionally, eccentric contractions of HAMS (4 reps) were also performed at 60º.s^{-1} and 180º.s^{-1} where the isokinetic dynamometer was set to the passive mode. Then, 4 maximal voluntary isometric contractions (MVIC) were recorded for both HAMS and QUAD with 30 seconds between trials. Isometric trials were alternated between HAMS and QUAD to prevent fatigue. To ensure an accurate assessment of maximal isokinetic and isometric strength, online visual feedback of the instantaneous dynamometer torque was provided to the subjects on a computer screen. Instructions were given to the subjects to perform all contractions as fast and forceful as possible to obtain both maximal torque and RTD. Trials with visible initial countermovement were excluded and a subsequent trial was added. The torque signals were A/D converted (MP100 – Biopac™ Systems, 16-bits) with a sample rate of 1000 Hz and low-pass filtered at 12Hz (zero phase shift 4th order Butterworth filter) using a custom-built routine for analysis (MATLAB version R2014b). All recorded torques were corrected for the effect of gravity on the lower limb.(AAGAARD et al., 1995)

Conventional and Functional H/Q ratios

Trials with the highest concentric and eccentric peak torque at both angular velocities were selected for analysis. The conventional H/Q ratio was calculated as the HAMS concentric peak torque divided by the QUAD concentric peak torque at both angular velocities and for MVIC ($H_{conc180}/Q_{conc180}$, H_{conc60}/Q_{conc60}, H_{MVIC}/Q_{MVIC}). The functional H/Q ratio was determined as the HAMS eccentric peak torque divided by the QUAD concentric peak torque ($H_{ecc180}/Q_{conc180}$, H_{ecc60}/Q_{conc60}). Also, the QUAD and HAMS isokinetic torques in a pre-selected knee joint flexion of 30º were selected for analysis and used to calculate the conventional ($H_{con180}/Q_{conc180}$@30º, H_{con60}/Q_{conc60}@30º) and the functional H/Q ratios ($H_{ecc180}/Q_{conc180}$@30º, H_{ecc60}/Q_{conc60}@30º) at long hamstring lengths.

Rate of Torque Development H/Q ratios

Rate of torque development (Nm/ms) for both QUAD and HAMS MVIC was calculated as the slope of the torque-time curve (i.e., Δtorque/Δtime) in incremental time periods of 50 ms starting from the onset of contraction, over five distinct time intervals (i.e., 0–50, 0–100, 0–150, 0–200 and 0-250 ms). The onset of force production was set as the time point where the torque exceeded baseline by 3 N.m(Aagaard et al., 2002; Maffiuletti et al., 2016; Opar et al., 2013) for both QUAD and HAMS muscles. The maximum torque-time slope at time windows of 20 ms(Rodríguez-Rosell et al., 2017), was then calculated to determine the peak rate of torque development (pRTD). The RTD H/Q ratios were calculated as described elsewhere (Zebis et al., 2011), by dividing the HAMS RTD by the QUAD RTD into the corresponding time intervals (for example RTD $H_{0\text{-}50}/Q_{0\text{-}50}$).

4.4. Statistical Analysis

Data are presented as means ± standard deviations (SD) unless stated otherwise. The distribution of all dependent variables was examined by Shapiro-Wilk test. When data did not meet the criterion of normal distribution, Wilcoxon signed-rank test was performed. A t-test for paired samples was used to compare pre and post-fatigue conditions and differences between groups (PI and UG) were tested by independent samples t-tests. Statistical significance was set at $P<0.05$. Cohen's *d* effect-size analysis was used to examine the magnitude of differences between groups (Cohen's d_s) and pre-and post-fatigue (Cohen's d_{av}) (Lakens, 2013). Threshold values of 0.2, 0.5 and 0.8 were used to represent small, moderate and large effects, respectively (Lakens, 2013). All data were analyzed using IBM SPSS Statistics (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp.).

4.5. Results

Subjects

No significant differences were found for height, body mass and body mass index. However, significant differences were found with respect to age (UG: = 22.6 ± 3.1 years vs PI = 26.6 ± 5.4 years, P=0.05, d=0.9). From the injured group, 66% of the injuries were located to the Biceps Femoris long head, whereas the other 33% were located at the medial hamstrings. Mean time since last injury was 10 months (range: 2-24 months) and mean time absent from practice was 5 weeks (range: 2-16 weeks).

Changes in Isokinetic and Isometric Strength. We found a significantly preferential effect of fatigue for the QUAD peak torque values in the UG at various angular velocities, 180º.s^{-1} (UG: Δ= -5.2 ± 6.9, d=0.6), 60º.s^{-1} (UG: Δ= -13.3 ± 21.4, d=1.1), 180º.s^{-1} at 30º of knee flexion (UG: Δ= -17.2 ± 12.2, d=1.2) and 60º.s^{-1} at 30º of knee flexion (UG: Δ= -11.4 ± 16.5, d=0.8). Also, significant differences between UG and PI were found for QUAD peak torque at 60º.s^{-1} (UG: Δ= -13.3 ± 21.4 vs PI: Δ=-3.9 ± 12.5, d=1.0) and QUAD peak torque at a velocity of 180º.s^{-1} at 30º of knee flexion (UG: Δ= -17.2 ± 12.2 vs PI: Δ= -3.5 ± 13.3, d=1.1). Additionally, both groups showed a significant change pre to post FAST-FP for HAMS peak torque at a velocity of 60º.s^{-1} at 30º of knee flexion (UG: Δ= -16.3 ± 23.0, d=0.6 and IG: Δ= -9.6 ± 16.0, d=0.3). Indeed, muscle fatigue is impaired differently between groups. The previously injured players showed a preferential HAMS weakness at long muscle lengths (30º of knee flexion) that differs between contraction type (eccentric > concentric), as well as at angular velocities (60º.s^{-1} > 180º.s^{-1}), whereas the UG showed a preferential HAMS concentric weakness (see table 4).

Table 4: Mean (± SD) per cent changes (pre- to-post-FAST-FP) Quadriceps (QUAD) and Hamstrings (HAMS) isometric and isokinetic data. Isokinetic Strength: concentric (CONC) and eccentric (ECC) peak torque, angle of peak torque and peak torque at 30º of knee flexion (@30º). Isometric Strength: maximal voluntary isometric contraction (MVIC) and peak rate of torque development (pRTD). Values are means ± SD.

			UG (n=12) Change (%)	PI (n=12) Change (%)	ES (*d*)
Isokinetic Strength					
	Peak Torque (N▪m)				
	QUAD CONC	180°.s^{-1}	-5.2 ± 6.9 [a]	-2.5 ± 6.4	0.4
		60°.s^{-1}	-13.3 ± 21.4 [a]	-3.9 ± 12.5 [b]	1.0
	HAMS CONC	180°.s^{-1}	-2.5 ± 16.9	-3.2 ± 10.3	0.1
		60°.s^{-1}	-12.5 ± 21.4	-5.1 ± 12.5	0.4
	HAMS ECC	180°.s^{-1}	-6.8 ± 15.4	-4.4 ± 18.5	0.1
		60°.s^{-1}	3.8 ± 21.4	-3.7 ± 13.9	0.4
	Peak Torque @30º (N▪m)				
	QUAD CONC	180°.s^{-1}	-17.2 ± 12.2 [a]	-3.5 ± 13.3 [b,c]	1.1
		60°.s^{-1}	-11.4 ± 16.5 [a]	-0.3 ± 13.3	0.7
	HAMS CONC	180°.s^{-1}	-5.6 ± 27.7	-4.0 ± 11.9	0.1
		60°.s^{-1}	-16.3 ± 23.0 [a]	-9.6 ± 16.0 [a]	0.3
	HAMS ECC	180°.s^{-1}	-11.4 ± 23.9	-8.6 ± 21.3	0.1
		60°.s^{-1}	-11.2 ± 27.2	-12.1 ± 17.6	0.0
Isometric Strength					
	Maximal Voluntary Isometric Contraction (N▪m)				
		QUAD MVIC	-7.3 ± 9.3 [a]	-1.7 ± 14.0 [c]	0.5
		HAMS MVIC	-12.6 ± 14.4 [a]	-7.6 ± 12.7	0.4
	Rate of Torque Development (N▪m/ms)				
		QUAD pRFD	-32.1 ± 18.3	-1.4 ± 29.0 [b]	1.3
		HAMS pRFD	-21.5 ± 24.3 [a]	-11.2 ± 29.0	0.4

[a] $P < 0.05$; significantly different from Pre to Post;
[b] $P < 0.05$; significantly different from the UG;
[c] Wilcoxon signed-rank test was performed;

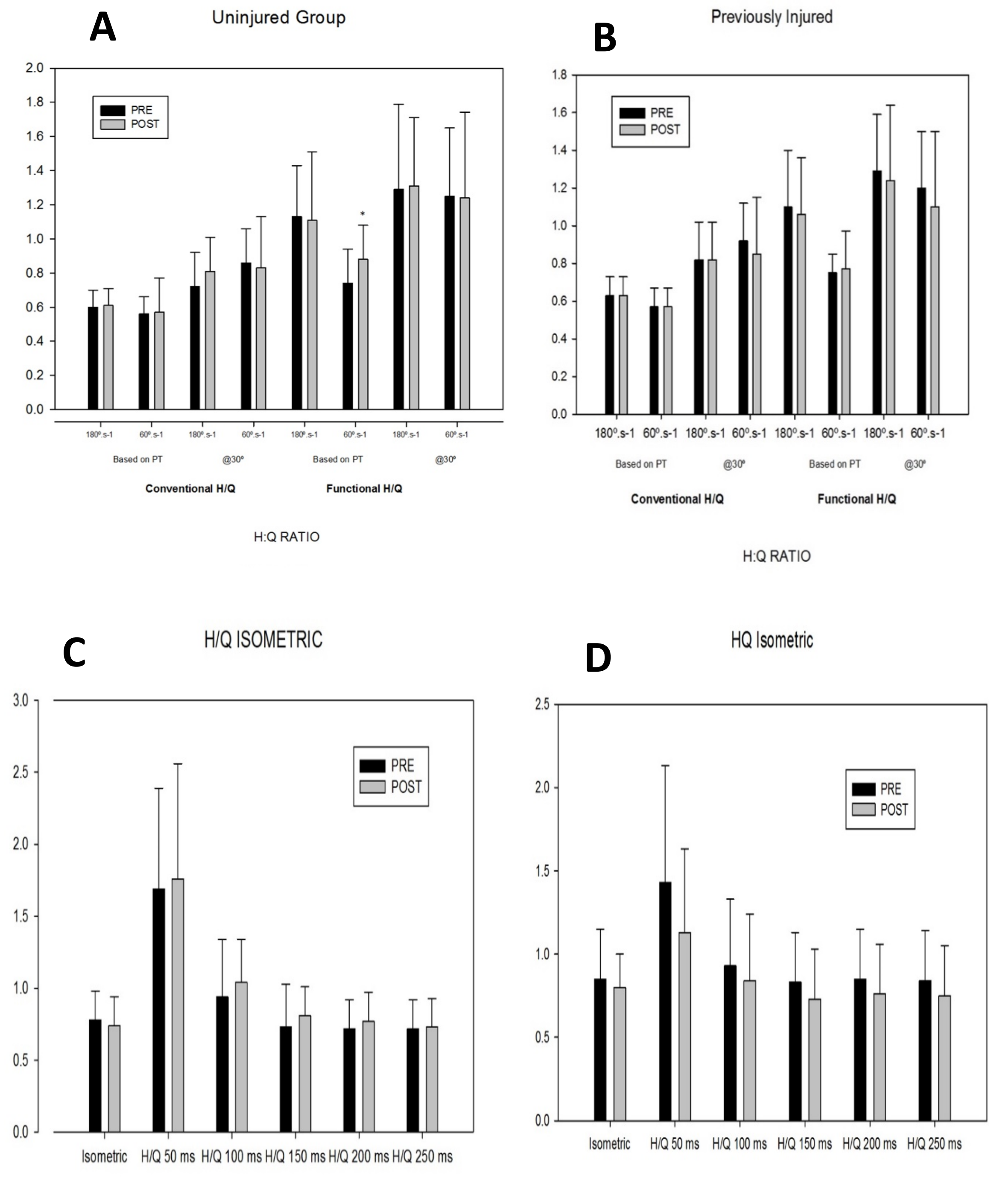

Figure 6: Hamstring-to-Quadriceps Ratios (H//Q ratios): Conventional and Functional H/Q ratios based on peak torque and @30º; RTD H/Q ratios based on incremental time periods of 50 ms before (Pre) to (Post) differences: * $P < 0.05$. Isokinetic H/Q ratios from the UG (A) and PI (B) groups; Isometric H/Q ratios from the UG (C) and PI (D) groups.

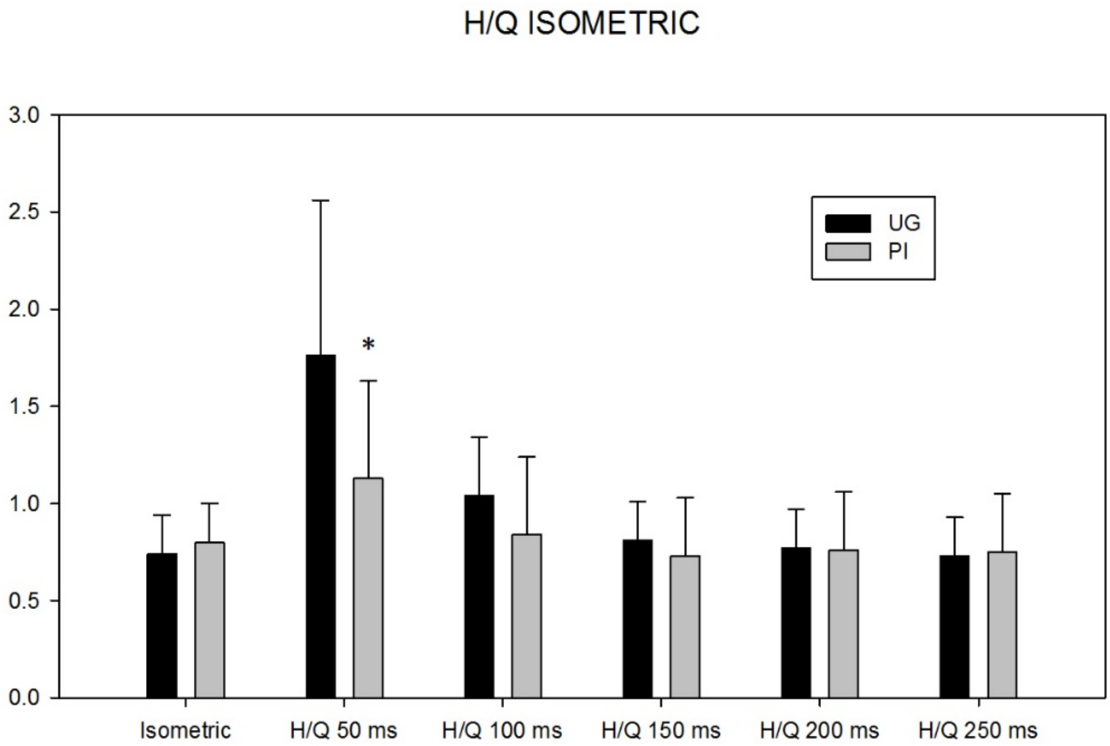

Figure 7: Hamstring-to-Quadriceps Ratios (H//Q ratios): Conventional and Functional H/Q ratios based on peak torque and @30º; RTD H/Q ratios based on incremental time periods of 50 ms before (Pre) to (Post) differences: * P < 0.05. Isokinetic H/Q ratios from the UG (A) and PI (B) groups; Isometric H/Q ratios from the UG (C) and PI (D) groups.

<u>Changes in Conventional, Functional and RTD H/Q ratio.</u> As a consequence of the higher QUAD weakness found for the UG following fatigue, a significant increase was found for the H_{ecc60}/Q_{conc60} (pre: 0.74 ± 0.2 post: 0.88 ± 0.2, *d*=0.7). Although no significant changes were found between groups, there is a moderate effect towards the PI group to show lower knee muscle balance at H_{ecc60}/Q_{con60} following fatigue (UG: 0.88 ± 0.2 vs PI: 0.77 ± 0.2, *d*=0.6). The same holds true for the remaining H/Q isokinetic ratios (see table 5 and figure 6). Figure 6 shows this inversion of knee muscle balance from PRE to POST fatigue.

A significant difference was also found between groups for the RTD H_{50}/Q_{50} following fatigue (UG: 1.76 ± 0.8 vs PI: 1.13 ± 0.5, *d*=1.0), showing a significantly lower muscle balance at 50 ms following the onset of contraction. Also, although not statistically significant (*P*=0.1), the previously injured players showed a moderately lower RTD H_{100}/Q_{100} following fatigue (UG: 1.04 ± 0.3 vs PI: 0.84 ± 0.4, *d*=0.6) and small effect towards lower RTD H_{150}/Q_{150} (UG: 0.81 ± 0.2 vs PI: 0.73 ± 0.3, *d*=0.3) (See table 5 and figures 6 and 7).

Table 5: Hamstring-to-Quadriceps Ratios (H/Q ratios): Conventional and Functional H/Q ratios based on peak torque and at 30º of knee flexion and RTD H/Q ratios based on incremental time periods of 50 ms, before (Pre) and after (Post) the FAST-FP.

				Pre	**Post**	**ES (*d*)**
H/Q Isokinetic Ratios						
Conventional (HAMSconc:QUADconc)	Based on Peak Torque	180°.s^{-1}	**UG**	0.60 ± 0.1	0.61± 0.1	0.0
			PI	0.63 ± 0.1	0.63 ± 0.1	0.0
		60°.s^{-1}	**UG**	0.56 ± 0.1	0.57 ± 0.2	0.1
			PI	0.57 ± 0.1	0.57 ± 0.1	0.0
	@30º	180°.s^{-1}	**UG**	0.72 ± 0.2	0.81 ± 0.2	0.6
			PI	0.82 ± 0.2	0.82 ± 0.2	0.0
		60°.s^{-1}	**UG**	0.86 ± 0.2	0.83 ± 0.3	0.1
			PI	0.92 ± 0.2	0.85 ± 0.3 [c]	0.3
Functional (HAMSecc:QUADconc)	Based on Peak Torque	180°.s^{-1}	**UG**	1.13 ± 0.3	1.11 ± 0.4	0.1
			PI	1.10 ± 0.3	1.06 ± 0.3	0.1
		60°.s^{-1}	**UG**	0.74 ± 0.2	0.88 ± 0.2 [a,c]	0.7
			PI	0.75 ± 0.1	0.77 ± 0.2	0.1
	@30º	180°.s^{-1}	**UG**	1.29 ± 0.5	1.31 ± 0.4	0.0
			PI	1.29 ± 0.3	1.24 ± 0.4	0.1
		60°.s^{-1}	**UG**	1.25 ± 0.4	1.24 ± 0.5	0.0
			PI	1.20 ± 0.3	1.10 ± 0.4	0.3
H/Q Isometric Ratio						
Based on Peak Torque @30º			**UG**	0.78 ± 0.2	0.74 ± 0.2	0.2
			PI	0.85 ± 0.3	0.80 ± 0.2	0.2

table 5 continuance

			Pre	Post	ES (*d*)
H/Q RTD Ratios					
Based on incremental time periods of 50 ms	H/Q 50	**UG**	1.69 ± 0.7	1.76 ± 0.8	0.1
		PI	1.43 ± 0.7	1.13 ± 0.5 [b]	0.5
	H/Q 100	**UG**	0.94 ± 0.4	1.04 ± 0.3	0.3
		PI	0.93 ± 0.4	0.84 ± 0.4	0.2
	H/Q 150	**UG**	0.73 ± 0.3	0.81 ± 0.2	0.3
		PI	0.83 ± 0.3	0.73 ± 0.3	0.3
	H/Q 200	**UG**	0.72 ± 0.2	0.77 ± 0.2	0.2
		PI	0.85 ± 0.3	0.76 ± 0.3	0.3
	H/Q 250	**UG**	0.72 ± 0.2	0.73 ± 0.2	0.1
		PI	0.84 ±0.3	0.75 ± 0.3	0.3

Values are means ± SD;

[a] $P < 0.05$; significantly different from Pre to Post;

[b] $P < 0.05$; significantly different from the UG;

[c] Wilcoxon signed-rank test was performed;

4.6. Discussion

To the best of our knowledge, this is the first study investigating the acute effect of fatigue, induced by the FAST-FP, on the rapid hamstrings to quadriceps ratio in professional football players with previous hamstring strain injury. The main findings of this study were that muscle fatigue affects differently maximal muscle strength and rate of torque development. Although, maximal strength of previously injured hamstrings is poorly affected by fatigue, the ability to produce large amounts of force in the initial contraction phase (i.e. explosive strength) seems to be significantly affected.

Football is characterized by intermittent shifts of intensity occurring every few seconds, involving explosive-type muscle actions like jumping, tackles and sprints (Mohr, Krustrup, & Bangsbo, 2003). Thus, the ability to generate rapidly high amounts of muscle force (i.e., exerting a high rate of force development) is an important performance indicator and can also represent a protective injury mechanism for HSI. Moreover, the effects of fatigue in RTD is of considerable interest, as HSI incidence is augmented in the last third of each halves of a football match (Woods, 2004). Based on the time-wise nature of the proposed mechanism of HSI (Heiderscheit et al., 2005; Thelen et al., 2005; Yu et al., 2008) and the temporary pattern of injury (Woods, 2004), we hypothesized that evaluating the RTD H/Q ratio at different time intervals and under a fatigued condition would be more appropriate to determine muscle mechanical properties of previously injured hamstrings.

While no significant differences were found for maximal muscle strength following fatigue, a possible eccentric contraction weakness at an angular velocity of 60º.s^{-1} was found at long hamstring lengths (i.e. peak eccentric torque at 30º of knee flexion). Similar results were found in previous studies, were preferential hamstring eccentric weakness were found in acute fatigue induced by an intermittent running protocol (Greig, 2008; Rahnama et al., 2003), in professional football players with no known history of HSI. It was being hypothesized that the greater HAMS eccentric weakness following fatigue can be explained by ultra-structural damage or maladaptation following injury (Fyfe et al., 2013). If we consider the injurious high-speed running, and specifically the late swing phase (Heiderscheit et al., 2005; Thelen et al., 2005; Yu et al., 2008), it seems suggestive that this preferential hamstring eccentric weakness could be a predisposing risk factor for (re-)injury. Also, our evidence that such eccentric weakness was exacerbated at long hamstring lengths is in accordance with previous studies that found a selective inability to activate the hamstring at long muscle lengths

(Sole et al., 2011). These results can also explain the high incidence of HSI during the last moments of each half of the football match (Woods, 2004), where fatigue plays a crucial role in reducing eccentric hamstring strength, which is preponderant for the injurious late swing phase.

Explosive muscle strength of previously injured hamstrings declined significantly at the very initial phase of muscle contraction (50 ms) after fatigue. Given the aforementioned reduced time to perform explosive movements (50-250 ms) and the need to rapidly decelerate the advancement of the thigh during the final movement phases (Chumanov et al., 2011; Thelen et al., 2005), the rate of force development of the hamstring muscles (or rate of torque development, as measured isometrically in our study), could have important implications during the injurious late swing phase. Thus, the evidence found in our study for a decreased ability to rapidly activate the hamstring muscles at long muscle lengths under fatigue, could enhance the susceptibility to undergo a strain injury and supports the concept that HSI usually occur during the final stages of each half of the match (Woods, 2004). Therefore, it is essential to measured not only peak torque but also the RTD in order to analyze the potential risk of HSI during rapid match situations.

Thorlund et al. (2008) found similar preferential RFD decline following a simulated handball match with elite handball players (Thorlund et al., 2008). However, more recently the same authors did not found any significant differences in the decline of MVC and RFD following a soccer match-play with young football players (Thorlund et al., 2009). Some different physiological mechanisms are underlying to maximal muscle strength and rate of force development (Aagaard et al., 2002; Andersen & Aagaard, 2006; Greco et al., 2013). While the early phase of the muscle contraction (<75 ms) is more dependent of increased neural drive, the later phase of the torque-time trace (>75 ms) is more correlated with MVIC and muscle contraction velocity properties, such as muscle fiber composition (Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2017). Also, fatigue following a football match is mediated by a combination of central and peripheral factors (Rampinini et al., 2011). Thus, our findings are suggestive that previously injured hamstrings have an decreased neural drive at early muscle contraction following fatigue, which alters the H/Q RTD ratio and enhances the susceptibility to injury during the late moments of a football match. We hypothesize that this possible decrease in neural drive, found in previously injured hamstrings, could be caused by neural inhibition due to the pain mechanism, which reduces the agonist muscles activation and strength (Graven-nielsen, 2008), and by the constraint of avoiding hamstring lengthening during early rehabilitation (Fyfe et al., 2013). Also, a concomitant atrophy of the biceps femoris long head (the most common strained hamstrings muscle in football) and hypertrophy of the short head of the biceps femoris was described as a musculotendon remodeling following a HSI (Silder et al., 2008). The reduction of the biceps femoris long head in-series sarcomeres and concomitant increase in pennation angle (Timmins Et Al., 2017; Timmins, Shield, Williams, Lorenzen, & Opar, 2015) has been linked to an increased susceptibility to (re)injury (Timmins et al., 2016). These findings are consistent with our hypothesis of injured muscle neuromuscular inhibition. In fact, a hypertrophy of the short head of the biceps femoris after HSI suggest a selective redistribution of mechanical stress over the hamstrings muscles, such as Semimembranosus and Semitendinosus and Biceps Femoris short head. These altered neuromuscular pattern is of paramount importance, as it changes hamstring torque generation capacities which could affect the RTD in previously injured hamstrings.

4.7. Perspective

This was the first study the effect of fatigue in the RTD H/Q in professional football players with previously injured hamstrings. Our results showed significant differences between groups, towards a reduced RTD H/Q at the very initial phase of muscle contraction (50 ms) as well as moderate and small effects at 100 and 150 ms, respectively. These results set the basis for future studies to measure neuromuscular capabilities in previously injured hamstring players with different methodologies, as electrically evoked stimulation. Also, prospective studies should seek to investigate whether previous lowered RTD H/Q are present in football players that sustain an HSI or if it is a maladaptation following injury. Finally, future investigation should seek to study the effect of the location of injury, muscle group and its location within the muscle (i.e. proximal, distal) and whether this can affect the hamstring strength capabilities following injury.

4.8. References

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Chapter 5: General Conclusion and Perspectives

GENERAL CONCLUSION AND PERSPECTIVES

Given the questions presented in chapter 1 we can conclude that:

1. Despite no statistical significance, the previously injured group showed a small to moderate effect towards lower rapid hamstrings to quadriceps ratio at long muscle lengths, in an unfatigued condition, at the very initial phase of muscle contraction. This results, although no statistically significant, shows us that rate of force development (or rate of torque development) could have important implications in the rehabilitation or prevention of hamstring strain injuries in football players.

2. Previously injured players presented higher concentric peak torque values, in fact, in some cases, results show a small to moderate higher concentric peak torque values for the PI group. On the contrary eccentric peak torque values in previously injured hamstrings showed moderate effect towards a preferential eccentric weakness. This results are consistent with those found in the literature, whereas a preferential hamstring eccentric weakness is found in previously injured hamstrings. This results suggests that possible neuromuscular inhibition can occur at long muscle lengths which can be harmful for the proposed mechanism of injury (eccentric contraction at late swing phase) increasing the susceptibility to injury. Again, we reinforce that these results lack statistical significance, maybe cause due to the small sample size.

3. Regarding the conventional and functional hamstrings to quadriceps ratio, previously injured players showed higher knee muscle balance at an unfatigued state. These

results suggest that assessing knee muscle balance based on peak torque could not discriminate injury risk or previous injury. We hypothesize that this can be due to the different time available to attain maximal muscle strength (~500 ms) and the one available in explosive type movements (~50-250 ms) such as those present in football (i.e. high-speed running, kicking, jumping). Also, the most perpetuated mechanism of injury (i.e. high-speed running) occur in a much lower time constraint (~50-250 ms).

4. Finally, regarding the effect of acute fatigue, previously injured hamstrings were preferentially impaired in eccentric contractions at long muscle lengths as well explosive strength. Whereas the UG were predominantly impaired in peak torque concentric contractions and maximal voluntary contractions. These results suggest that fatigue can impair explosive muscle contraction at long muscle lengths of previously hamstring muscles which can result in a lowered knee muscle balance. Again, these results showed a preferential impairment of rapid muscle strength in previously injured hamstrings, which suggests that future research should focus on rapid force generation and knee muscle balance, rather than peak torque based strength.

5. These results set the basis for further investigation around the explosive hamstring strength and HSI incidence as, now, we should seek to understand whether this is an adaptation to injury or a predisposing factor. Also, significant attention should be given to the location of injury and it’s adaption on hamstrings muscles force

generation capabilities, as this can promote different rehabilitation and prevention approaches.

Limitations

Two limitation were found in the study, that should be addressed in future investigations.

First, regarding sample size, a reduce sample was used in the present investigation. This is a common limitation when participants are professional athletes with dense calendars. However, assessing previously injured professional football players is of significant importance. First, because they are more likely to have access to a comprehensive rehabilitation. Second, injury history is more accessible and trustworthy, as medical departments are highly professional and organized. Third, they are more likely to have access to strength training and, fourth, more familiar with isokinetic evaluation. However, future studies should seek to have a larger cohort of professional football players.

Second, regarding the fatigue protocol chosen. The protocol chosen seek to mimic the load and characteristics of football however it lacks some fundamental technical gestures of football, such as kicking and tackling. Also, the volume is different from that found in 90 min of a football match. However, the time available to evaluate professional athletes is short and have to be carefully thought.

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